# ANALYSIS OF INFORMATION SYSTEMS FOR HYDROPOWER OPERATIONS

Jet Propulsion Laboratory

A REPORT TO
THE OFFICE OF
ENERGY PROGRAMS
NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION

SEPTEMBER 1976

5040-44

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FOR HYDROPOWER OPERATIONS

RTOP 777-30-01

September 1976

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

The purpose of this document is to summarize and provide a framework that unifies the diverse segments of the analysis. As such, it serves as an Executive Summary with conclusions and recommendations, · and as a guide to the study approach and methodology.

General Objectives and Scope

The general objective of this study was to analyze the operations of hydropower systems, with emphasis on water resource management, to determine how aerospace derived information system technologies can effectively increase energy output. Better utilization of water resources was sought through more accurate reservoir inflow forecasting based on use of hydrometeorologic information systems with new or improved sensors, satellite data relay systems, and use of optimal scheduling techniques for water release.

Study Approach

The principal guideline for the study approach was to develop a qualitative and quantitative understanding of the interrelations between hydropower operations and the supporting hydrometeorologic information systems. To accomplish this, specific mechanisms for improving energy output were determined, primarily the use of more timely and accurate inflow information to reduce spillage due to short term high inflow events. (This type of spillage is a dominant loss factor for a major class of hydropower installations.)

The present study differs significantly from the prior studies both in the methods for reducing spillage, and consequently, in the analysis approach. Prior studies have concentrated primarily on the seasonal aspects of spillage; percentage reductions in total seasonal spillage were assumed, and cost benefits derived on the basis of these reductions. Specific mechanisms by which improved information systems could bring about these reductions were not defined, however, improved predictions of long term, seasonal precipitation are implied. Improvements in such predictions are quite speculative at present, and detailed, quantitative analyses of advanced information

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systems for this purpose are somewhat premature. This in fact has been the dilemma encountered in prior studies.

The present study established at an early stage in the analysis that, for a large number of major reservoirs, spillage is a dynamic, short term phenomenon attributable to unanticipated high inflow events. This type of spillage can be reduced in direct proportion to the number of days of anticipation (0 to 20 days) and to the accuracy of the inflow forecast. By defining the problems in these terms, specific methods for reducing spillage could be identified and their potential assessed. Basically, two techniques are useful for short term inflow prediction: the first is weather forecasting, and the second, use of empirical modeling techniques to simulate runoff from the snowpack and ground hydrologic system. Both techniques provide estimates of the amount and time of arrival of inflow (in most watersheds, moisture input to the snowpack/ ground hydrologic system requires several days to reach the reservoir). Both processes can be modeled. Further, we can establish the sensitivities of the model outputs to errors in the measured variables. These sensitivities form the basis for sensor and overall information system requirements: which variables must be measured, with what accuracies and how frequently; what is the desired density of the sensor network; how quickly must the inflow predictions be disseminated to the hydropower operators; and, what modifications to the models would improve the predictions. Finally, having determined sensor requirements, sensor capabilities can be compared to requirements, and a sensor set selected that best meets these requirements.

This approach has been used in the present study to define in a quantitative manner the spillage loss mechanisms and the benefits that can reasonably be expected from improved information/sensor systems, and to provide guidance for sensor R&D programs and the supporting data acquisition, transmission, processing and dissemination subsystem developments. The analysis activities were supplemented by many contacts with industry and government hydropower operators, who provided much useful data as well as the basic computerized hydrometeorological models; the latter are particularly valuable because they are based on actual operational policies and constraints.

For convenience in presenting the results of the work, the analysis tasks are described below:

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1) Characterize hydropower operations relating to energy production. (Hydropower generation is governed by a variety of water release constraints, and a high degree of variability in the water inflow to the reservoir.)

2) Identify mechanisms responsible for less-than-optimum production, principally spillage resulting from lack of timely and accurate inflow information. Estimate benefits derivable from the forecast of high inflow events, and resulting reduction in spillage. (The reduction in spillage for a major class of reservoirs is shown to be related to the number of days of anticipation of high inflow events, and to the accuracy of inflow forecasts.)

3) Identify the principal processes that contain information about the time of arrival and magnitude of high inflow events, primarily the meteorologic and watershed ground and snowmelt runoff processes. Acquire models of the hydrometeorologic processes (weather forecast and ground/snow hydrologic models) from industry and government sources.

4) Determine the sensitivities of the hydrometeorologic models to uncertainties or errors in the model variables, i.e., influence of sensor system accuracy on the accuracy of predicted inflow magnitude and arrival time.

5) Establish information/sensor system requirements to achieve a desired accuracy in inflow prediction.

6) Survey the capabilities of state of the art and advanced information/ sensor system elements to determine feasible concepts for improved information systems.

7) Develop an improved information system concept.

This approach to the analysis of hydropower systems is reflected in the following discussion.

Characteristics of Hydropower Operations

Major hydropower storage reservoirs in the United States must operate efficiently with inflow rates that can vary greatly from month to month and

season to season. In addition, releases from the reservoirs are governed by
a number of constraints relating to the delivery of power, delivery of water
for irrigation, navigation, water quality control, etc., and the observance of
adequate flood reservations. A number of important aspects of hydropower
operations are shown in Figure 1.
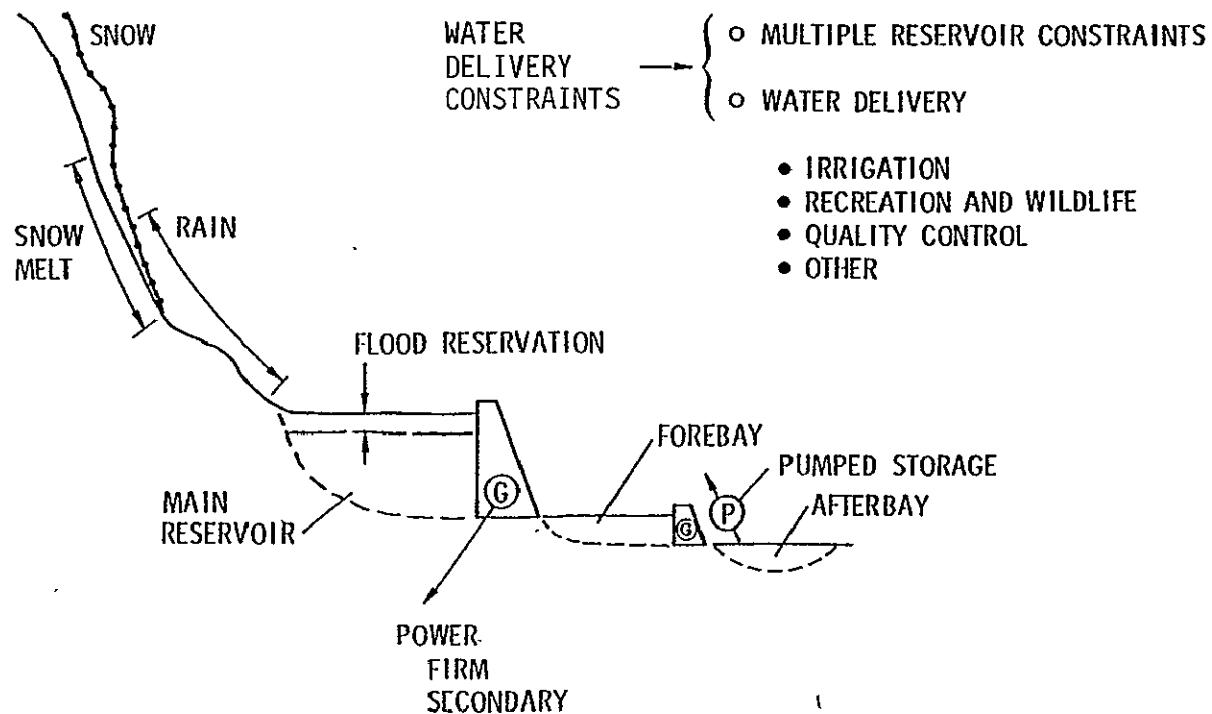
Figure 1. Hydroelectric Power System.

Sources of inflow to the hydropower system include melt from snow-
packs, rain, and drainage from the ground hydrologic system. Each source
of inflow has a characteristic lag time that is dependent on the physical char-
acteristics of the basin and on the state of the snow and ground hydrologic
systems; knowledge of these lag times can be of use in scheduling water
releases for the reservoir, but they are difficult to measure because of the
complex, non-uniform topography of the basin.

Of the numerous constraints, the flood reservation rules are vigor-
ously enforced; federal laws govern the use of the reservoirs constructed
with federal funds, and stipulate that a prime consideration in reservoir man-
agement is prevention of flooding, or minimization of damage due to flooding
through use of flood plains in conjunction with the reservoirs. Flood rules

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are established for each reservoir on the basis of historical inflow records, and typically specify storage volumes that must be set aside to accommodate peak inflows, given the current storage levels, expected inflows, and surface moisture conditions. The set aside volumes can be a significant fraction of the active storage available in the reservoirs.

The reservoir operator usually is contractually obligated to produce specified amounts of power and energy during a season, based on historical records of water availability; this is known as firm power. Contracts are also taken for secondary power delivery, contingent upon water availability. Target deliveries are established for each month and each day; release schedules are made down to the hourly level.

The basic advantage of hydropower generation is the relative ease of varying the power output level, in contrast to large fossil-fueled nuclear generation systems that are operated at fixed output when possible. In mixed systems using both hydropower and fossil-fuel or nuclear generation units, the hydropower generators are used to provide peak loads, thus permitting the fossil/nuclear plants to run at constant output near peak efficiency. In fact, the economies of operation are such that many reservoirs have been equipped to operate in a pumped energy storage mode, in which water releases from the main reservoir to meet peak loads are retained in an afterbay and pumped back into the main reservoir during periods of lower power demand. Power can be purchased from the system at a relative low rate for this purpose.

Water delivery constraints and agreements are noted in Figure 1. Additional constraints can be imposed for multiple-reservoir systems such that releases from upstream reservoirs do not exceed inter-reservoir channel capacities, or impair downstream reservoir operations.

Figure 2 illustrates a major difficulty in scheduling water releases caused by the wide variation in inflow during the course of a season. Typically, inflow is at a minimum during the late summer and early fall months, when the snowpack is depleted and rainfall is at a seasonal low. The snowpack accumulates during the winter months, but may not contribute significantly to inflow because little if any melt occurs during this period. During the spring months, considerable rainfall may occur, and with the onset of warm weather and heavy snowmelt, inflows tend to peak sharply during a relatively short period
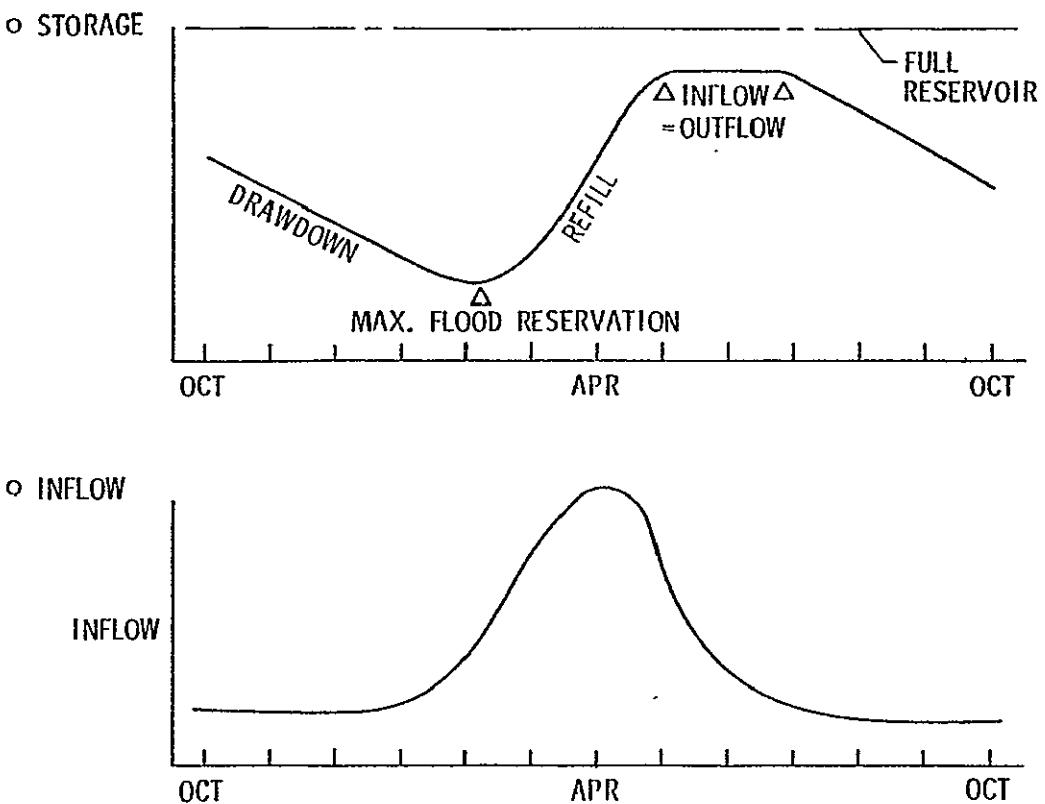
Figure 2. Reservoir Operations.

of several weeks. The actual levels of inflow can vary significantly from season to season. The storage level in the reservoir is managed in such a way as to enter the dry season with a nearly full reservoir so that power and water delivery commitments can be fulfilled during the dry season. A critical management period is encountered during refill since refill rates are heavily dependent upon forecasted inflows. If inflows are overestimated, adjustments late in the refill cycle may not be adequate to compensate for excessive early-season releases. Conversely, underestimates of inflow may lead to excessive spillage as the reservoir reaches maximum storage levels. The wide variations in inflows experienced at Shasta are shown in Figure 3, which compares monthly inflows for the 1973 and 1974 seasons. The monthly as well as seasonal variations in inflow emphasize the difficulties of water resource management for large, multi-purpose storage reservoirs. Daily and weekly variations within the monthly inflows contribute to the problem, particularly in controlling spillage.
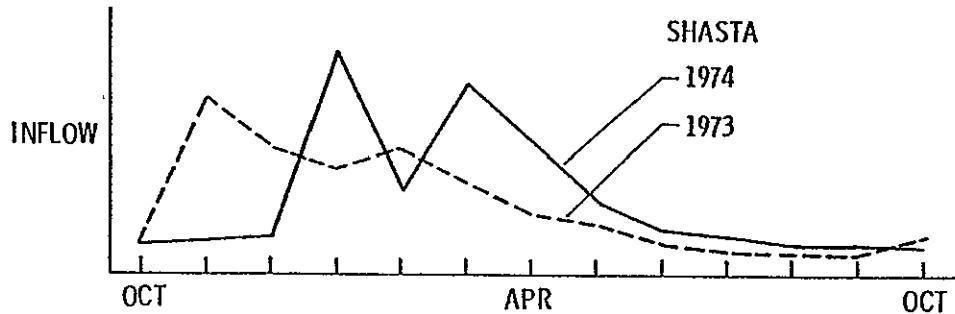
Figure 3. Inflow Variation

Prior Studies

Many studies over the past 8-9 years have addressed the potential for improving hydropower operations through the use of advanced information systems, based principally on the use of air/spaceborne sensors to improve the accuracy of predicting reservoir inflows. These studies generally were designed to provide guidance and support for remote sensor R&D programs by assessing the potential cost/benefits of applying these sensors to hydropower operations.

The principal loss in hydropower operations identified by the prior studies was spillage, i.e., release of water over spillways to avoid encroachment of flood reservations.[1] In a majority of studies historic reservoir release records were obtained on one or more major hydropower systems, and the total spillage summed for the season. The resulting loss of water was used as the basis for estimating the dollar benefits that could be realized if spillage were eliminated.

This general approach provides an upper bound estimate on potential benefits, assuming that mechanisms exist for reducing spillage. The usual mechanism put forth was an improvement in the accuracy of the prediction of total seasonal precipitation. Such improvements are quite speculative at present, and benefits derived on this basis tend to be over-estimated.

The results of six key cost/benefits studies are summarized in Table 1; these studies cover nearly a decade of activity in this area since the PRC effort was initiated in 1967. For each study the table give the estimated annual

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1. That fraction of the reservoir storage volume that must be reserved for a flood event.

Table 1. Review of C/B Studies (Satellite Based Systems).

STUDY	ANNUAL BENEFITS (MILLION $)		BASIS	ANALYSIS TECHNIQUE	EXTENSION TO U.S.
PRC-1969 (GRAND COULEE)	HYDROPOWER FLOOD IRRIGATION (U.S.)	94 305 282 688	PERFECT SEASONAL INFO, NO HEDGE, OPTIMAL DRAWDOWN & REFILL, PERFECT KNOWLEDGE OF IRRIGATION DEMAND, RIVER LEVEL REDUCED TO MINIMIZE FLOODING.	UPPER BOUND ESTIMATES	TYPE AND SIZE OF RESERVOIR, IRRIGATION ACREAGE, FLOOD LOSSES IN U.S.
EARTH SAT CORP - 1974 (HUNGRY HORSE)	HYDROPOWER (WESTERN STATES)	10 - 28	PARAMETRIC VARIATION OF SEASONAL FORECAST ACCURACY	SIMPLIFIED SIMULATION OF DRAW & REFILL	RATIOED BY KWHRS
ECON - 1974 (OROVILLE)	HYDROPOWER IRRIGATION (WESTERN STATES)	42.0 8.6 50.6	ASSUMED A 20% REDUCTION IN FLOOD RESERVATION.	UPPER BOUND ESTIMATES	RATIOED BY KWHRS
MICH (1974) (PALISADES)	IRRIGATION (PALI)	.38-.76	PERFECT INFO FOR SHORT TERM (30 DAYS) AND LONG TERM.	SIMULATION MODEL (DAILY)	
*ECON (1975-1) (OROVILLE)	HYDROPOWER IRRIGATION	.6 2.2 2.8 (ORO) 19.2 (U.S.)	PARAMETRIC IMPROVEMENTS IN SHORT TERM (30 DAY) FORECAST.	SIMULATION MODEL (WEEKLY)	ALL WATERSHEDS WITH 811 KAF, 200 MW, 1000 GWHR, LARGE SNOW PACK.
ECON (1975-2) (SHASTA, GRAND COULEE, HOOVER, + 6 WESTERN RESERVOIRS)	HYDROPOWER IRRIGATION FLOOD	.65 .34 --- .99	FRACTION OF UPPER BOUND ESTIMATES.	UPPER BOUND ESTIMATES	(AS IN 1975-1). NOTE: SHASTA DOES NOT MEET CRITERIA, BUT CONTRIBUTES 33% OF BENEFITS.

*ALSO CONCLUDED THAT IMPROVED MEASUREMENT OF SNOW PACK DOES NOT IMPROVE FORECASTING SIGNIFICANTLY.

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benefits for reducing or eliminating spillage; the basis for the estimate, the analysis technique; the extension of the case study results (Grand Coulee, Oroville, etc.), to the entire United States; and the extent to which forecasting techniques were analyzed, if at all.

As an example, the ECON 1974-75 studies were based on analyses of Oroville operations on the Feather River. The early study (1974) simply assumed that the flood reservation could be reduced 20% through improved forecasting. Since the total flood reservation can reach 750,000 AF (over one-third of the active storage volume of the reservoir), projected benefits due to a 20% reduction in the reservation are very substantial. No specific mechanisms were identified or hypothesized for achieving the improvement in forecasting. In actuality, the flood reservation at Oroville is based on accommodating a "maximum" storm event, 9 inches of rain in approximately 4 days. To reduce the flood reservation, it would be necessary to establish <u>with a high degree of confidence,</u> that a major storm could be forecasted both as-to the time of occurrence and amount of precipitation. Weather forecasting techniques cannot achieve the necessary accuracies since forecast scores decrease rapidly beyond the first 24 to 36 hours, and decrease with increasing amounts of precipitation. Hence, the ECON-1974 benefits assumptions are optimistic. Extrapolating the benefits based on the Oroville case study to a large number of other hydropower systems is unrealistic.

The ECON 1975-1 study, also based on Oroville, is a significant improvement over prior analyses in that the benefits are related to forecast period, i.e., days of anticipation, and accuracy. These results provide a clue as to the role of short term inflow forecasting in hydropower operations. Unfortunately the investigators did not extend this analysis to examine short term inflow forecast techniques, which involve streamflow synthesis and weather forecasting, both of which can provide a limited number of days of anticipation. The ECON 1975-1 study went on to estimate benefits based on perfect information, and extrapolated the results to other hydropower plants meeting certain criteria related to storage and generating capacity, and fraction of inflow derived from snowmelt. The resulting total estimate of benefits for all watersheds is questionable.

The ECON 1975-1 report also concluded that more accurate measurements of snowpack water content would not increase hydropower output at

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Oroville because such improvements would not lead to better estimates of total remaining inflow for the season, i.e., could not contribute to perfect long term inflow predictability, which they had previously identified as the only means for improving hydropower output. This conclusion is inappropriate for several reasons. First, hydropower output can be enhanced if short-term forecasting (2 - 20 days) can be improved, since, as will be shown, measurements of the snowpack are vital to short term, dynamic forecasting. Secondly, other investigators have shown some correlation between the areal extent of snowcover and percent of the remaining seasonal inflow; if these correlations can be established with reasonable confidence for given river basins, the information might be used to reduce flood reservations, although an adequate data base is not currently available. Finally, major hydropower systems in the Pacific Northwest have relatively heavier snowpacks, which places greater emphasis on accurate knowledge of the snowpack; the general applicability of the conclusion is therefore questionable.

The ECON 1975-2 study perpetuates the "upper bound" approach to benefits analysis used in prior studies with the same assumptions and conclusions. A more sophisticated attempt was made to extrapolate the benefits estimates to major reservoirs in the Western States, but the approach did not address the dynamic, short term nature of spillage, nor the capabilities and limitations of information systems that must be relied upon for high inflow anticipation.

In summary, prior studies have consistently based benefits estimates on an assumed percent reduction in total spillage over a season; the levels of reductions were arbitrarily chosen, and not related to an assessment or analysis of information system capabilities or constraints. The dynamic, short term nature of spillage, which is usually caused by unanticipated high inflow events, was not fully represented in the analyses, although the ECON 1975-1 study developed a relation between benefits due to spillage reduction and days of forecast with various degrees of forecast accuracy. As a result of the over emphasis on seasonal forecasting, information systems techniques providing short term inflow forecasts were not identified, and hence, not properly evaluated; further, the ground and snow hydrologic system models,

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and weather forecast techniques upon which such information systems must be based, were not identified nor analyzed except by PRC, however, PRC did not relate inflow lag times and weather forecastability to spillage reduction potential. Admittedly, information systems cannot hope to achieve perfect forecastability in the foreseeable future, but with improved hydrometeorologic models, better anticipation of high inflow events is achievable; benefits due to spillage reduction through short term forecasting will not be large compared to the upper bound seasonal limits, but the potential gains are not insignificant.

An outcome of prior studies has been the failure to provide proper guidance to information systems R&D programs, particularly those dealing with air/spaceborne sensors. Too few analytical studies of remote sensor applications to hydrometeorological information systems are available, particularly those that address the difficulties of measuring and interpreting key variables for complex snow and ground hydrologic systems in non-uniform mountainous terrain. Results obtained over level, uniform topography have been too easily extrapolated to the far more difficult hydrologic systems associated with hydropower operations. Future studies must be oriented to address these factors.

Analysis of Hydropower Operations

The first, and critical task in the present study was to develop a more detailed understanding of real time reservoir operations to serve as a basis for establishing information system requirements, and to determine under what conditions and to what extent better inflow information can improve hydropower production.

The American River basin in the Sierra Nevada range was selected for analysis because the reservoir at Folsom was representative of major multi-purpose reservoirs operating under highly variable inflow conditions described previously. Folsom is a moderately large installation of 200 mw installed capacity with 1,010,000 acre feet of storage. Spillage is an important loss factor, but moderate production gains are possible through

spill reduction. Inflow release records are available for Folsom for a representative number of years.

An immediate question arises as to optimum release strategies given a forecast of inflows for a particular planning period, say, one month. With no forecast capability, the operator must rely on historical records to formulate daily release schedules for the month. The release schedule is subsequently adjusted to account for differences between the expected and actual inflows. Simulations are frequently used to assist the operator in maximizing the hydropower output within the constraints related to flood reservations, contractual water and power delivery, etc. Improved information forecasting enables the operator to develop better release schedules, such that less variation between expected and actual inflow is experienced, and fewer adjustments required. The operator has available to him weather forecasts, estimates of water content and condition of the snowpack, soil moisture condition, and some forewarning of storms. Perfect information about future inflows tends to maximize the system output, provided a methodology is available to the reservoir manager to make best use of the information.

Researchers at UCLA (Drs. Yeh and Becker) recently developed a dynamic programming technique under the Bureau of Reclamation sponsorship to optimize releases for real time reservoir operations, given water and energy release targets for the month and day. This program has been computerized for application to operations at Folsom, and provides an accurate and consistent tool for evaluating the benefits of improved information systems.

This dynamic programming methodology was used to analyze the potential benefits to hydropower operations at Folsom for improved inflow information over a range of forecast periods, including the upper bound case of perfect accuracy over a given period. The program maximizes the benefits of improved inflow information, since it provides the optimal strategy for releases under specified constraints.

The results are shown in Figure 4 in terms of benefits in GWHRS as a function of days of anticipation with perfect information. For example,

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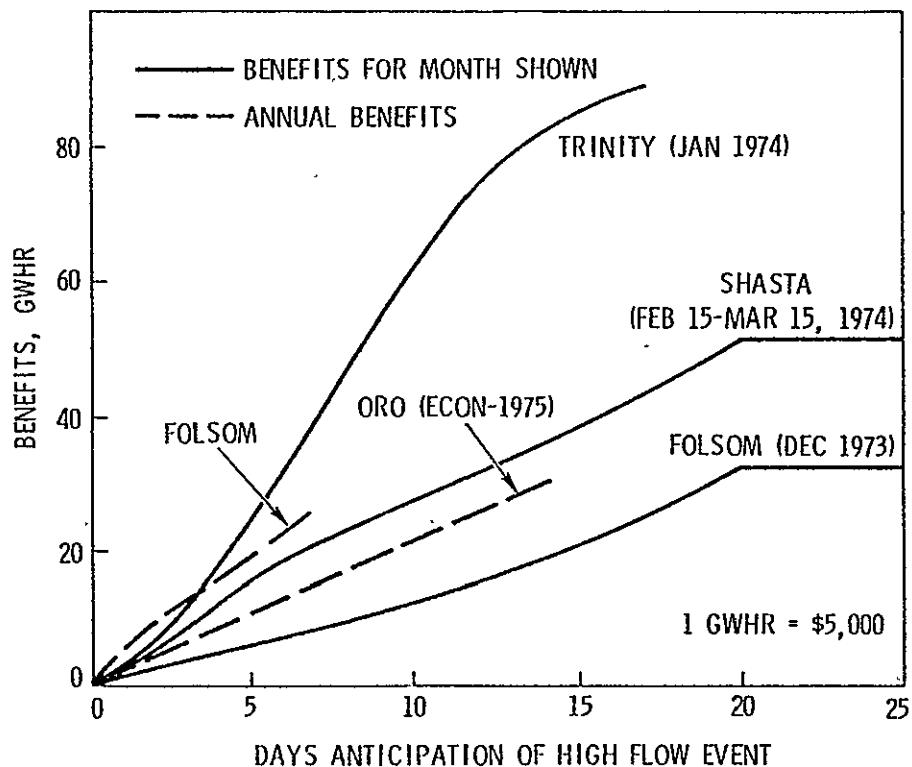
Figure 4. Hydropower Benefits Central Valley Project.

prediction of inflow with 100 percent accuracy for a period of 7 days at Folsom would yield a benefit of 7.6 GWHRS for a month over actual energy generation. Folsom currently sells energy to the net at $5,000 per GWHR, hence the benefit for the month is $38,000. If the anticipation time is extended to 20 days with 100 percent accuracy, benefits increase linearly to 33 GWHRS over actual production. Extension of anticipation time beyond 20 days results in little further improvement in energy production.

Annual benefits at Folsom were estimated, based on 10 years of operational data. For an anticipation time of 7 days, annual benefits are approximately 28 GWHRS or a net annual increase in energy production of 2.7 percent; the annual value of the increase is $140,000.

The benefits analysis was extended to two other storage reservoirs in the California Central Valley, Shasta and Trinity. The approximately linear relationships between the benefits and days of anticipation for these reservoirs

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are very similar to that derived from Folsom. Also, nearly all the potential benefits are achieved with 20 days of anticipation. An approximate extrapolation to all Northern California units on the basis of installed capacity gives a total potential benefit of 600 - 800 GWHRS for 7 days of anticipation.

An analysis was also made of major hydropower plants on the main stem of the Columbia River, which have about half the total capacity in the Pacific Northwest system, and about 25 percent of the nation's total hydropower capacity. Seven years of detailed historical records were obtained for these plants. An analysis of the data brought out several distinct patterns. Spring and summer runoff from snowmelt is dominant; rainfall runoff also contributes to the high spring inflows. The second characteristic is the continued heavy spilling during the high inflow season arising from the disparities between maximum hydropower releases and the very heavy spring inflows. Frequent below-maximum power releases were also noted while simultaneously spilling water, due primarily to insufficient load demand by the present power markets. It was estimated that the following average annual benefits could be obtained from anticipation of high inflows, provided that maximum power releases could be made:

Chief Joseph to Priest Rapids

1 day anticipation	49.0 GWHR
2 days anticipation	92.9

McNary to Bonneville

1 day anticipation	23.4 GWHR
2 days anticipation	59.6

Grand Coulee

1 month anticipation	250.0 GWHR

In summary, spillage is attributable primarily to random, high inflow events that cannot be accommodated entirely within the reservoir, and which exceed the capacities of the power turbines. If accurate advance warning of high inflow events is available, storage levels within the reservoir can be

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reduced in advance of the events, approximately in proportion to the number of days of anticipation.

The forecast must be of relatively high accuracy to be of benefit to the hydropower operator, since releases on the basis of low probability forecasts are generally considered too risky.

Since reduction of spillage is dependent upon inflow forecasting accuracy, i.e., days of anticipation, a knowledge of lag times for ground and snow hydrologics systems is required. Parameters and variables affecting the lag times must be identified, and ranked in terms of their relative importance. An assessment must be made of the capabilities of instrument systems to measure the many variables affecting lag times. Similarly, assessments must be made for weather forecasting techniques, since these also provide for a limited number of days of anticipation. The results can then be compared to benefits versus anticipation time as shown in Figure 4 to establish a realistic although approximate estimate of potential benefits.

Inflow Forecasting

Inflow forecasting relies upon three basic models, including the ground hydrologic system, the snowpack hydrologic system, and weather forecast. Each has been analyzed to determine the characteristic lag times, accuracy, and suitability for real time estimation using ground based and/or remote sensors.

A schematic of a typical ground hydrologic systems is presented in Figure 5. The system is comprised of various elements of a complex hydrologic cycle involving percolation, soil mositure storage, drainage and evaportranspiration. The hydrologic system model calculates each component of run-off (surface run-off, interflow and baseflow), using a concept of moisture accounting for upper zone tension and free water, and lower zone tension and free water.

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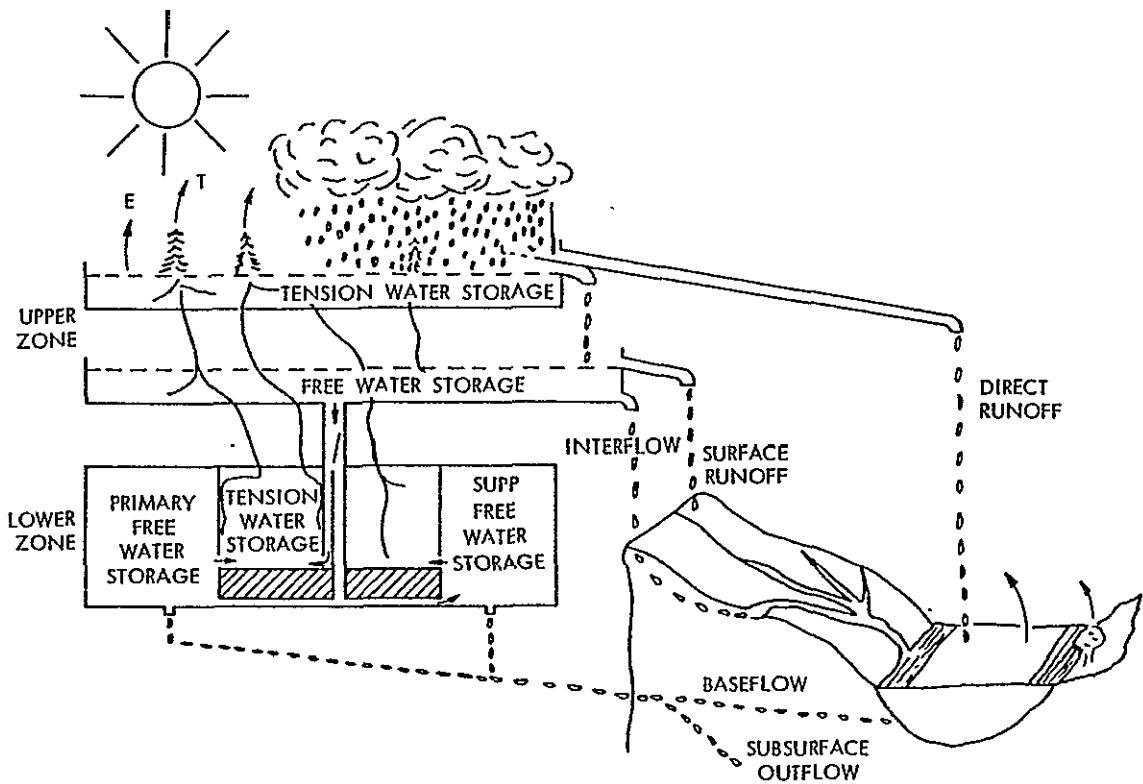
Figure 5. A Generalized Hydrologic Model (GSSS).

The basic parameters and variables used in the hydrologic model, include:

- Initial conditions

  Upper zone tension and free water content

  Lower zone tension, primary free and secondary free water content

- Precipitation (rainfall and snowmelt)

- Evaportranspiration demand

- Watershed parameters

  Impervious area

  Drainage and percolation rates

  Lower zone tension and primary and supplemental free water storage capacities

and several parameters related to the various processes simulated by the model such as surface runoff, interflow, base flow and channel storage.

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Snowmelt runoff poses complex problems for inflow predictions. It is not adequately handled in any of the several available inflow models, which generally assume that snowmelt enters directly into the ground hydrologic system, and is therefore equivalent to rainfall in terms of moisture input. In actual fact, snowmelt may not enter the ground hydrologic system as the melt occurs, but can be retained in the snowpack for days and weeks before entering the ground system. This is a serious shortcoming in the existing inflow prediction methods that should be emphasized in snow hydrology research programs.

Unlike rainfall, snowmelt is not generally measured quantitatively, but must be estimated indirectly from observation of the snowpack. The Stream-flow Synthesis And Reservoir Regulation (SSARR) model developed for the Columbia River basin, uses a snowmelt predictor based on several melt components including those related to short wave and long wave radiation, convection and condensation, rain, and ground state. The observables include: air temperature, dew point temperature, wind, solar radiation and albedo. An inventory of snowmelt accumulation and melt can be computed for the basin, sub-basin, or for snow bands, which are zones of relatively equal altitude. The approach is designed for mountainous watersheds that pose particular difficulties in inflow prediction.

The sensitivity analysis was performed for the American River watershed in the Central Sierra Nevada's, using the General Streamflow Synthesis System (GSSS) inflow model for the ground hydrologic system processes and the SSARR model for the snowmelt functions (the former model does not include a detailed snowmelt component). Based on the sensitivity analysis, the relative importance of the several parameters and observables was determined for a representative period of operations in the basin (March 1957) at Folsom. The results are given in Table 2 for three sets of variables, those related to the watershed, input and initial conditions, and snowmelt parameters.

The most important watershed parameters were found to be the lower zone water storage capacity, amount of water required to fill non-impervious areas, and percolation rates. None of these parameters are amenable to direct measurement by remote sensors, and for the most part, must be determined indirectly by variance minimization techniques.

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Table 2. Sensitivity Analysis.

a. Sensitivity Analysis ($\Delta V/V$).

Ranking	Watershed Parameters (GSSS)	% Change in Streamflow / % Change in Parameters
1	P_5, Lower Zone Free Water Storage Capacity	-3.8
2	P_3, Lower Zone Tension Water Storage Capacity	-3.5
3	P_1, Depth of Water to Fill the Non-Impervious Area	-1.3
4	P_9, Percolation	-1.2
5	P_4, Lower Zone Supplemental Free Water Capacity	-1.2
6	P_6, Upper Zone Lateral Drainage Rate	1.2
7	P_{10}, Shape Factor for Percolation	1.2
8	P_{12}, Upper Zone Free Water	1.1

b. Sensitivity Analysis ($\Delta V/V$).

Ranking	Input Parameters and Initial Conditions	% Change in Streamflow / % Change in Parameters
1	MI, Moisture Input (Precip + Snowmelt), MI	4.0
2	I.C.3, Lower Zone Tension Water Contents	3.8
3	I.C.5, Lower Zone Primary Free Water Contents	2.9
4	I.C.1, Upper Zone Tension Water	1.3
5	I.C.4, Lower Zone Supplementary Free Water	0.60
6	Evapotranspiration	-0.10

c. Sensitivity Analysis ($\Delta MI/MI$).

Ranking	Snowmelt Parameters	% Change in Melt Rate / % Change in Parameters
1	P_1, Snow Covered Area	-0.5
2	P_{14}, Air Temperature	-0.2
3	P_{17}, Insolation	-0.1
4	P_{13}, Precipitation	-0.1
5	P_{16}, Albedo	0.05

The most important input parameters are: moisture input (rainfall and snowmelt), and lower and upper zone water content. The latter parameter is amenable to remote sensing, and has an impact on the accuracy of inflow prediction. Snowmelt is an important function and its measurement is one of the few to which remote sensing can contribute. Of the several snowmelt variables, areal extent is one of the most important; remote sensing has been employed for measuring snowpack areal extent with good success when not limited by cloud cover. The other high ranking variables generally are not amenable to remote sensing.

In summary, watershed hydrologic models are highly empirical in nature, and utilize a large number of variables in estimating stream flow. Many of these are determined indirectly by variance minimization techniques; few are amenable to direct measurement by remote sensing. It can also be observed that a highly accurate measurement of a single variable will have little effect on overall inflow prediction because of the large variances associated with the remaining variables; it probably will not be cost effective to pursue costly remote sensing developments that improve the measurement accuracy of only one or two variables. Sensor requirements must be established on the basis of overall system accuracy improvement, and used as the basis for sensor R&D programs. The extremely complex non-uniform nature of mountainous watershed hydrologic systems imposes severe constraints upon the effectiveness of remote sensing for inflow prediction.

Initial conditions and watershed variables are expressed as single lumped parameters; this contributes sources of errors in prediction since in nature the parameters are distributed. The errors can be minimized by dividing the watershed into sub-basins, each with its own set of parameters. This approach requires considerably more information, but improvements in accuracy may demand models that better represent the spatial variations in hydrologic systems characteristics.

The hydrologic system modeling techniques provide little information on a critical factor in hydropower operations, viz., the prediction of inflow lag. The GSSS model estimates the lag in the American River basin to be 4 days. The model does not distinguish the differences in lag between direct

and base flows, or differences that obviously depend on the state vector of the hydrologic system, which varies greatly over the runoff season. It also does not differentiate between the lags of the different sub-basins; a single lumped value is calculated. The possible inaccuracies associated with this highly empirical approach to lag time estimation are evident.

Synoptic Inflow Models

The LANDSAT Multi-Spectral Scanner (MSS) imagery program has led a number of investigators to test various synoptic inflow models which relate seasonal runoff to the areal extent of the snowpack. Using MSS data in the visible and IR bands, the fraction of the basin covered by snow is measured during the late winter and spring runoff seasons, and related to the accumulated runoffs at start of heavy snow melt. Good correlation has been found for the few cases tested, and appears to warrant further study. The technique unfortunately has not proved successful in the Columbia River basin because of extended periods of cloud cover, which prevent the accumulation of sufficient data.

The synoptic model relating accumulated seasonal runoff to snow covered areas does not by itself provide dynamic inflow data, i. e., it cannot be used to predict inflow and thus help avoid spillage. Snowmelt models based on energy balance techniques as described earlier are required for this purpose. However, flood reservations for some reservoirs are based in part on expected total seasonal runoff; if the synoptic models can provide such information with a high confidence level, flood reservations could be reduced, with significant increases in hydropower production. For this reason, some research efforts should continue in this area.

Weather Prediction

Weather prediction provides the second primary method for anticipating high inflow events. Several meteorological variables are important in predicting inflow, including precipitation (type, amount, and spatial distribution), and those related to snowmelt: air temperature, insolation, wind, humidity, etc. Key questions pertain to how accurately these variables can be predicted, what advances can be expected in prediction accuracy, and which variables are amenable to remote sensing.

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Two basic approaches are taken to prediction of meteorological variables, statistical and physical modeling. The statistical model ignores physical dynamics and uses historical measurements of dependent variables and several independent variables. Such a model in general cannot predict time variations, and is used more frequently for seasonal estimating.

The physical modeling approach utilizes the physical laws that govern the complex dynamics of the atmosphere, and include thermodynamic equations, the equations of motion, equations of state, and continuity of mass. Solutions to these resulting complex nonlinear equations can be obtained by large-scale computer program. Such models are suitable for short-range forecasts, but are questionable for prediction periods of more than a few days.

Recently, some researchers have combined the physical and statistical approaches. The Model Output Statistics (MOS) technique developed by the National Weather Service is an example. This technique consists of determining a statistical relationship between a predictand and variables forecast by a numerical (physical) model over some time period. It is particularly useful in matching observations of local weather with outputs of numerical models. The biases in numerical models as well as local climatology can be accounted for in the forecast.

The National Weather Service is applying an MOS model to the Columbia River basin. The representative equations have been developed for forecasting warm season precipitation and temperature, both of which can contribute to impoved forecast accuracy.

The general levels of accuracy attainable with MOS techniques are shown in Table 3. Table 3a shows the forecast accuracy for precipitation amounts for various forecast periods and amounts of precipitation. The accuracies tend to drop off significantly beyond the first 24 to 36 hours. A more discouraging aspect from the standpoint of predicting high inflow events is the sharp reduction in accuracy for heavy precipitation, i. e., rain of one inch or more. This characteristic also precludes the possibility of reducing flood reservations, which are dictated by worst case inflow events; to reduce flood reservations, it would be necessary to demonstrate a capability to predict worst case high inflow events with high confidence. This clearly is not possible in the foreseeable future.

Table 3a. MOS — Prediction of Precip Amount.

STATIONS

FORECAST, F

HIT, H

OBSERVED, O

$$ACCURACY = \frac{H}{F + O - H}$$

(PERFECT SCORE = 1.0)
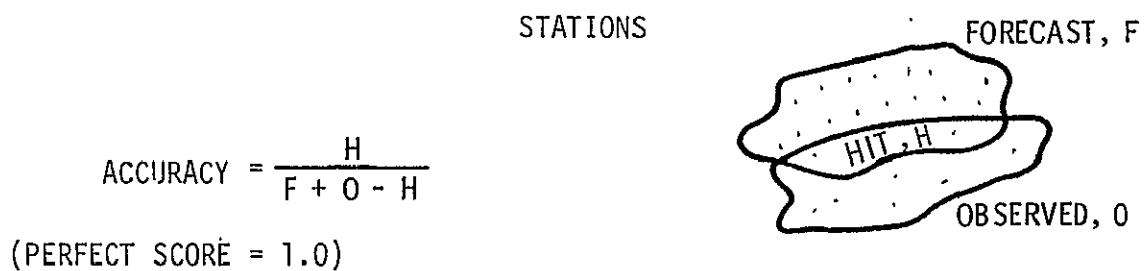
THREAT SCORE (NOV 75)					
	0.5"	1"	2"	3"	4"
12-36 HRS	.33	.17	.01	0	0
24-48	.26	.13	.02	0	0
36-60	.23	.11			

Table 3b shows the accuracy of max-min temperature predictions compared to past methods. Although not analyzed in the present report, it would be appropriate to relate the accuracy of max-min temperature forecast to the sensitivity of SSARR type inflow models to air temperature accuracy.

It is possible that the MOS technique is sufficiently accurate to serve as a source of information for several important snowmelt variables, including humidity, wind and insolation. Although the precipitation amount cannot be predicted with a high degree of accuracy, inflow is more dependent on snowmelt in the Pacific Northwest region, which is a major producer of hydropower. Further research along these lines is appropriate.

Recent analysis of numerical weather forecasting models at JPL indicates some of the difficulties of improving multi-variant predictor techniques. Using a numerical (physical model), the variance of one input variable, surface wind, was reduced, with the expectation that the accuracy of the overall model would be improved. To the contrary, the model tended to damp out the variances in the input values of surface wind, such that no improvement in forecast accuracy was achieved. Reduction in bias errors in input values might yield better results. These studies are continuing.

Information Systems Requirements

Based on the knowledge of spill mechanisms, and the relationship between spillage reduction and the inflow anticipation time and accuracy, quantitative requirements were developed for information systems designed to support hydropower operations. These requirements were stated in terms of the accuracies of key variables used in the ground hydrologic and snowmelt models that are employed to predict the amounts and rate of inflow into the reservoirs. Because many key variables contribute to the variance in inflow prediction, all such key variables must be measured with a relatively high degree of accuracy to achieve overall gains.

General and specific requirements have been devloped for sensors. The general requirements include:

- High confidence predictions of imminent rainstorms or rapid snow-melt events within a time frame that permits effective control action is desirable. Once a day sensing is necessary.

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Table 3b. Verification of Objective Maximum/Minimum Temperature Forecasts,
Averaged at 126 Cities, made twice a day, from Operational Prognostic Data by
MOS and Perfect Prog (PP) Systems. Winter Season (Oct. 1973 — Mar. 1974).

Projection	Type	Mean Absolute Error (°F)		Correlation of Forecast with Observed Temperature	
		MOS	PP	MOS	PP
24 h	Max	3.6	4.5	0.87	0.81
36 h	Max	4.4	4.8	0.82	0.78
48 h	Max	4.9	5.4	0.79	0.76
60 h	Max	5.3	5.7	0.74	0.72
24 h	Min	4.3	4.7	0.80	0.77
36 h	Min	5.1	5.1	0.76	0.71
48 h	Min	5.2	5.2	0.73	0.73
60 h	Min	5.8	5.7	0.67	0.67

- Accurate spatial sampling of precipitation and climatic variables is necessary to reduce sampling errors.

- An accurate assessment of soil moisture content is desirable. Weekly sampling is necessary.

- Knowledge of snowpack ripeness or maturity is of great importance where snowmelt is a significant contributor to runoff. This would indicate the imminence of substantial snowmelt runoff. A measurement frequency of several days during peak melt season is satisfactory. Resolutions of 1 km or less are necessary for non-uniform mountainous watersheds.

- Snowpack areal extent is a key variable in most snowmelt models, and should be included in information system implementations. An accuracy of 100 m is desirable.

- Data acquisition, transmission, processing, and dissemination on a timely basis is mandatory for prompt control action; slow turn-around time greatly reduces the value of the data. Data should be available to the operator in no more than 24 hours.

In deriving a quantitative error budget for measuring key variables, we note that errors can be allocated in any number of ways to produce an improvement in hydropower operations. An optimum error budget would take into account the total cost effectiveness of sensor and information system R&D program; since this data was not available, accuracy requirements have been parameterized for a representative basin, the American River in the Central Sierra Nevadas. The results are shown in Table 4 for 3 and 7 days of anticipation, and 2 levels of hydropower output improvements, 10 and 20 percent, respectively. Generally, instrumentation errors must be reduced by 5 to 15 percent to achieve the desired increases in hydropower output.

Sensor Capabilities

The preceding discussion has established requirements for sensor systems for inflow forecasting, and has articulated the mechanisms through which the sensors can contribute to improved hydropower operations. Based

Table 4. Allowable Parameter Estimation Errors.

Parameter	If 7 Days High Inflow Anticipation Possible[3]				If 3 Days High Inflow Anticipation Possible[3]			
	10% Benefit Decrease		20% Benefit Decrease		10% Benefit Decrease		20% Benefit Decrease	
	Prorated[1] Benefit Decrease %	Maximum Error %	Prorated[2] Benefit Decrease %	Maximum Error %	Prorated[1] Benefit Decrease %	Maximum Error %	Prorated[2] Benefit Decrease %	Maximum Error %
Precipitation (Water on Soil)	4.1	2.0	11.4	4.0	4.1	2.0	10.8	7.0
Upper Zone Soil Moisture	4.1	2.7	11.4	6.2	4.1	2.0	10.8	9.0
Snow Covered Fraction of Basin	4.1	3.4	11.4	7.8	4.1	3.0	10.8	13.0
Basin Insolation	4.1	11.0	2.0	5.0	4.1	8.0	4.0	8.0
Wind Speed	4.1	12.0	2.0	7.0	4.1	9.0	4.0	10.0
Albedo of Snow Pack	4.1	18.0	2.0	9.0	4.1	9.0	4.0	15.0

[1] Equally distributed benefit change budget, errors assumed to RMS to total benefit decrease.

[2] As above, but with second set of 3 parameters restricted to smaller budget to limit maximum errors.

[3] Reference benefit values = 27.5 GWH and 12.5 GWH, respectively.

on these stated requirements, a review of sensor capabilities was performed to determine the adequacy of present sensors (primarily in situ instruments), and the potential for application of air/spaceborne sensors to hydrometeorological information systems.

The results of the survey are summarized in Table 5, which lists those parameters that can be measured directly or remotely, and those that must be determined indirectly by variance minimization techniques. For the measurable parameters, the types of in situ sensors currently in use or under development are indicated; the feasibility of measuring the parameters by remote sensors (air/spaceborne instruments) is also noted. The relative ranking of the parameters in terms of their effect on inflow prediction is included in the table.

Of the key variables, all but snowpack areal extent can be measured by ground based sensors; photo imaging is well suited to measuring snowpack area, provided adequate cloud-free viewing time is available. These sensors can also measure the relatively stable physiographic parameters of the basin, such as forest cover areas, impervious areas, and surface drainage characteristics. Ground sensors must be used for other measurable parameters.

Ground Sensors. Treating the ground sensors first, the standard precipitation gages suffer the perennial problems of catch deficiency due to wind, improper shielding, and inability to account for the rain to snow ratio.

Snowpack depth, density and water equivalent are usually obtained manually with cutting tubes at specific sites along a snow course. The accuracies of such measurements are generally adequate. Snowpack structure cannot be determined, however. Pressure pillows are now used in many locations to measure water equivalence and (if depth is known) average density. A 12-ft rubberized pillow, filled with an anti-freeze solution, suitably installed, is the minimum size that will produce adequate weighings of the snow without experiencing considerable ice bridging of the pillow. Accuracies without ice bridging are within ±10 percent. Development work is continuing in this area.

Measurement of snow depth with the use of unattended sensors has not been satisfactorily resolved. Pole markers are usually distributed throughout the basin and observed from low-flying aircraft, however, the operation may be too risky to undertake with any reasonable frequency.

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Table 5a. Field Measurable Parameters.

Variable	Runoff Sensitivity Ranking [3]	Instrumentation	Comments	Currently Amenable to Remote Sensing	Potential for Remote Sensing
Precipitation	High	Standard rain and snow gages	Location and sampling problems	No	Storm anticipation, areal distribution possible, microwave.
Snowpack Areal Extent	High	Photo-imaging	Satellite sensing although limited by cloud cover.	Yes	
Upper Zone Tension Water	High	Electrical resistance meters	Calibration problems	No	L-band or lower frequency microwave, upper 10 cm possible.
Impervious Fraction Basin	Low	Photo-imaging	Frozen soil under snow not sensed	Sometime — see comments	
Water Surface Fraction	Low	Photo-imaging	Static parameter	Yes	
Forest Cover Fraction	Low	Photo-imaging	Static parameter	Yes	
Mean Overland Surface Length	Low	Photo-imaging	Static parameter	Yes	
Streamflow	High	Standard streamgage		No	
Insolation [1]	Low	Pyrheliometer	Field problems	No	
Air Temperature	Medium	Thermograph		No	
Humidity [1]	Low	Hygrothermograph or psychrometer	Field problems	No	
Albedo of Pack [1]	Low	Back to back pyrheliometers	Impractical for field	No	Possible correlation with active microwave reflected signals.
Wind Speed [1]	Low	Anemometer		No	
Snow Depth [2]	⎫	Snow survey/pole markers/radioisotope profiler	Sampling problems	No	⎫
Snow Water Equivalence [2]	Parameters not in model	Snow survey/pressure pillow/radioisotope profiler	New developments	No	Depth averaged snowpack characteristics sensing by active or passive microwave requires further theoretical and sensor development and test. Good potential.
Snow Liquid Water Content [2]		Microwave profiler	New development	No	
Snow Density [2]	⎭	Snow survey/radioisotope profiler	New development	No	⎭

1. Parameter not generally used for day to day operation because of data inadequacy.

2. Parameter not generally used in current watershed models.

3. High sensitivity corresponds to absolute value ≥ 1.
   Medium sensitivity corresponds to absolute value < 1. and ≥ 0.5.
   Low sensitivity corresponds to absolute value < 0.5.
   (See Tables 5-7 to 5-9.)

Table 5b. Non-Measurable, High Sensitivity Model Parameters.
(listed in order of sensitivity ranking)

Relative Rank	Variable
1	Lower Zone Free Water Storage Capacity
2	Lower Zone Tension Water Contents
3	Lower Zone Tension Water Storage Capacity
4	Lower Zone Primary Free Water Contents
5	Depth of Water to Fill Non-Impervious Area
6	Percolation
7	Lower Zone Supplemental Free Water Capacity
8	Upper Zone Lateral Drainage Rate
9	Percolation Shape Factor
10	Upper Zone Free Water

In addition to depth and water equivalence, some knowledge of snowpack structure is highly desirable, but remains one of the most difficult phenomena to measure. As noted previously, snowpack structure can change markedly as it matures during the season; the snowpack can absorb large quantities of water, either rainfall or snowmelt, without releasing the water to the ground hydrologic system and hence to the reservoir. Conversely, a minor rainfall or snowmelt event can trigger a large water release from a ripe snowpack. Hence, the "state" of the snowpack is of vital concern to the reservoir operator.

A profiling snow gage is being developed to obtain better estimates of rain and meltwater runoff. The gage consists of a gamma radiation source and scintillation detector that traverse in two parallel vertical tubes through the snowpack. The gage detects snowpack density over the height of the pack. Liquid water content is also of interest, however, calorimetric sensing methods are difficult to automate. In a development similar to the radioactive isotope density profiler, a microwave source and detector are capable of accurately measuring liquid water content. The two profilers operating together can give data as to pack structure, which when combined with climatic information, will enable accurate short term predictions of snowmelt runoff. While these profilers are not prohibitively expensive, simpler, less costly implementations would permit more extensive sampling, as well as application to more watersheds.

The other variables listed in Table 5 can be measured with state of art ground sensors, although adequate spatial sampling frequency is often limited by sensor and site implementation costs, ease of access for servicing, and data transmission facilities. The synoptic measurement potential of air/spaceborn sensors is clearly desirable if it can be exploited.

Visible and IR Sensors. Candidate remote, i.e., air/spaceborne sensors include visible and IR sensors, and passive and active microwave sensors. The application of visible/IR sensors for measurement of snowpack area has been discussed. Achievable accuracies of 100 m or better with LANDSAT MSS type instruments are quite satisfactory, but these sensors suffer from some basic operational limitations, principally the inability to penetrate heavy cloud cover, forest cover, and fog. Also, if the satellite vehicle is at low enough altitude for good imaging, the frequency of coverage may be low, and

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this characteristic exacerbates the problem with cloud and fog. Partial compensation is obtained with the use of multiple satellites and more than one type of sensor. A further difficulty is encountered in the transmission, reduction and dissemination of the large volume of image data. In addition, relatively low altitude satellite vehicles limit the basin size that can be observed per pass. Melting snow can be detected by observing the reflectance of snow in various IR bands, however, no quantitative data has been made available.

Passive Microwave. Snow emits small amounts of radiation at microwave wavelengths. Despite the low power, low resolution and complex patterns of the emissions, there is some indication that snow areal extent can be determined by current passive microwave radiometers without the operational problems of shorter wavelength radiometers. Microwave brightness temperatures of dry snow, wet snow, and snow-free terrain are sufficient that snow extent can be calculated either by snow-line mapping or by intergrating the brightness temperature values within a resolution element (requiring a number of frequency, polarization, and/or viewing angle considerations, depending on the number of different types of snow within the element). However, the latter method has not been demonstrated adequately; thin dry packs will allow radiation from the soil, degrading the measurement accuracy. It also appears that wet snow might be difficult to distinguish from snow-free ground or from dry snow.

Researches suggest that snow water content and water equivalence might be determined for dry snowpacks up to about 2 meters by judiciously varying frequency, polarization, viewing angle, etc., and noting changes in brightness temperature. These suggestions are speculative at the present time. The results of field and laboratory investigations and theoretical studies indicate that snowpack emissions vary with snow water equivalence but that moist snow may present problems in separating the effects of liquid water from those associated with water equivalence. In general, the useful application of microwave radiometry will depend on a better understanding of the bulk snow properties (volume scattering phenomena) and, possibly the properties of the soil layers.

L-band may be used to minimize the influence of vegetation and surface roughness on soil mositure measurements by passive microwave, but antenna

size would be a distinct problem. · The S194 L-band radiometer on Skylab appeared to correlate satisfactorily antenna temperatures with a 30-day antecedent precipitation index. This would relate to the top layers of soil; longer wavelengths would be required for deeper penetration.

At the wavelengths sensitive to subsurface moisture the resolution at orbit (460 km) is 30-150 km, not adequate for use in most watershed models. (Aircraft overflights are a possibility.) The corresponding resolution for sensing surface moisture is from 3-30 km. There is no available accuracy data although aircraft radiometric measurements over bare flat fields have yielded about 5 percent error for moisture contents of 10 - 40 percent.

The shorter wavelengths for surface moisture measurements are sensitive only to very thin surface layers, which can undergo wide diurnal fluctuations in near-surface moisture content.

In summary, it is difficult to reconcile the low resolution capabilities of passive microwave sensors with resolutions required to measure ground and snowpack parameters in mountainous watersheds with complex, non-uniform hydrologic systems. Sensors of this type are much more amenable to application to broad planar areas of uniform hydrologic makeup.

Active Microwave. Radars possess advantages over passive microwave in that they offer high spatial resolution through the use of synthetic apertures. However, these advantages are compensated by high complexity and cost. Active microwave sensors suitable for measurement of hydrologic parameters are presently being developed.

In principle some important physical properties of the snowpack can be obtained with multi-frequency radars (lossless and homogeneous layered media and normal incidence assumed). As frequency is varied, the reflection amplitude will go through cycles of minima and maxima. Noting these values and taking measurements before and after the first appreciable snowfall, snow and earth dielectric constants can be calculated from theoretical relationships. Snow depth can be determined from the snow dielectric constant and from values of the frequency at which the first minimum is encountered. The approximate average density of the dry pack also can be determined, but the density distribution of the pack cannot be determined. It is claimed that the

wetness (liquid water content) of a wet snowpack can be determined by the behavior of the reflection coefficient vs frequency, provided volume wetness is greater than 1 percent.

It is estimated that the snowpack depth and density can be obtained within a ±15 percent tolerance, however, this has not been demonstrated even under carefully controlled laboratory conditions with simple snowpack structures. It is not clear how the technique could hope to succeed when applied to mountainous watersheds with widely variable non-uniform snowpack structures. It is not clear how well wetness can be measured in lossy media although ripening of the pack might be noted adequately by time observations of approximately wetness measurements.

The microwave radiometric investigation of snowpacks by Aerojet-General Corporation is of particular significance in this connection, and indicates the complexities of snowpack microwave radiation and the consequent difficulties in interpreting radiometric measurements. The results of this investigation indicate that although empirical relationships between pack water equivalence and microwave emission were demonstrated, theoretical models which approximated subsurface snow structure could provide only rough qualitative explanations of measured results but no quantitative agreement. Such phenomena as ice and snow layers of varying densities and thicknesses, variable liquid water content, surface roughness, and the granular structure of the snow, and ground-pack interface were inadequately treated by the most sophisticated current snowpack models. These phenomena require a treatment of radiation scattering and emission by random media. In particular, emissions from wet snow varies with water equivalence in a complex fashion, and it was not possible to separate effects due to water equivalence from those due to liquid water. Further, soil emissions can penetrate substantial depths of snow so that information as to the nature of these emissions is important to the accuracy of snowpack measurements. Freezing and thawing of the soil and its moisture content produce significant effects. On the other hand, the study indicates that it may be possible to measure the water equivalence of dry snowpacks over a broad class of terrains by radiometric means. Also, there appears to be little polarization and radiation dependence on incidence angle over the angular range of interest and the terrain slopes common in mountain snowpack regions.

Soil moisture may also be sensed by multiple polarization radar. No accuracy assessment that would apply operationally is available. Difficulties may be encountered with surface roughness effects unless long wavelengths are used.

Conflicting results with side looking radar (SLAR) images of snowpack have been experienced. New snow and recrystallized old snow may not be seen.

In summary, it is not clear how microwave techniques can hope to succeed when applied to mountainous watersheds with widely variable non-uniform snowpack structures. A great deal of additional theoretical and experimental studies must be performed to justify the use of these sensors for present applications.

An Information System Concept

The preceeding discussion has indicated a number of deficiencies in current watershed runoff forecasting techniques, particularly forecasts intended for hydropower operations. Major inaccuracies result from rain-storm prediction and watershed and climatic parameter sampling errors, and from a failure to consider snowpack melt, maturation, and discharge phenomena in sufficient detail and with adequate instrumentation.

A runoff information system concept is outlined which will alleviate some of these deficiencies and improve hydropower day to day operations. It is clear that, for at least the 1970s, the bulk of the instrumentation must be ground based. However, since rapid data collection and dissemination is a necessity, automation and reliable hardline or telemetry (including satellite relay) of the data to a central operator are very desirable.

Watershed runoff and streamflow parameter sensing requirements are summarized in Table 6. The values given in Table 6 are primarily for the Sierra Nevada, in accordance with information obtained from Dr. James L. Smith, U.S. Forest Service at Berkeley. Climatic and topographical features are sufficiently regular and uniform throughout the area to permit a relatively sparse network. Regions such as the Pacific Northwest will require parameter sensing with approximately 2-4 times the density of

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Table 6. Sensing Requirements.

Parameter	Measurement Frequency	Measurement Sampling Density	Comments
Precipitation	Daily	3-10 per Basin	
Soil Moisture	1 per wk	1-2 per Basin	
Relative Humidity	Daily	1 per Basin	
Wind Speed	Daily	1 per Basin	
Air Temp	Daily	1 per Basin	
Snowpack Albedo	1 per 3 days	1 per Region	A "Region" will include several Basins.
Insolation	Daily	1 per Region	
Snowpack Area	1 per wk in winter 1 per 3 days during snowmelt season	Each Basin	
Snowpack Water Equivalence	Same as Area	3-10 per Basin	
Snowpack Depth	Same as Area	3-10 per Basin	
Snowpack Density	1 per wk in winter; daily during snowmelt season	1+ per Basin	Density profile with depth required
Snowpack Liquid Water Content	Same as Density	1+ per Basin	Profile required
Snow Temp	1 per 3 days	1 per Region	Profile desirable
Soil Temp	1 per wk	1 per Region	Will detect frozen ground surface.
Streamflow	Daily	1 per Stream	

Note: Density and liquid water depth profiles probably not required for cold and dry snowpacks such as in Rocky Mountains.

those given in Table 2-6. Accuracies of currently available instrumentation are considered generally adequate.

The number of hydrologic and climatic sensors can be minimized through use of a hierarchy of data collection stations, and the correlation of appropriate data elements between them. Table 7 shows the necessary sensors, stations, and costs for a wet snow regions typified by the Sierra Nevada. The first order stations serve as primary reference (base monitor) stations for a geographical area with similar climatic regimes, and containing a number of watersheds. The first order stations generally would be manned or periodically attended, and would be instrumented to gather all relevant watershed and climatic data. The second order stations collect all data required for normal operational use. First and second order data can be correlated, particularly with regard to snowpack melt phenomena to produce an accurate estimate of day to day snowmelt runoff. In turn, second and third order data correlations can reduce measurement errors arising from complex snowmelt phenomena. These phenomena are sensed by the third order station sensors, snow pillows, only in the aggregate. The manually obtained fourth order data serve as checks on the automatic instrumentation.

The preferred mode of data transmittal to the central facility is by satellite relay, although a detailed trade-off with conventional ground relay techniques is required to justify the use of satellite relay for specific watersheds. Data Collection Platforms (DCP) have been designed to operate with LANDSAT or GOES satellites in a data relay mode to transmit hydrometeorological information to designated ground receiving stations. The reliability of this mode has been demonstrated by LANDSAT to be comparable or better than ground based microwave relay systems. Furthermore, there can be significant cost savings; it has been estimated that a $3 million telemetry cost for the Pacific Northwest HYDROMET installation in the Willamette Valley could be reduced to $1 million by using the GOES data relay system.

The total cost of data collection platform, power supply, and instrumentation (exclusive of multispectral scanner and manual surveys) for the range of stations given in Table 7 (and assuming 10 basins per region) is estimated to be $600,000 - $2,500,000 if DCPs are used for the third order stations. However, the higher cost value may be an overestimate since

Table 7. Sensor and Station System Concept (Sierra Nevada).

Parameter	Sensor	Order of Station				Estimated Cost per Unit $1,000
		1st 3 per Region	2nd 1 per Basin	3rd 3-10 per Basin	4th 15-20 per Basin	
Precipitation	Heated Precip Sensor	X	X	X		1.2
Soil Moisture	Electrical Resistance	X	X			0.5
Rel. Humidity	Hygrometer	X	X			0.6
Wind Speed	Anemometer	X	X			0.7
Air Temp	Thermocouple	X	X			0.7
Albedo Insolation	Pyroheliometer — Two Req'd	X				1.2 for 2 units
Snow Area	Satellite-borne Multispectral Scanner					
Snow Water Equivalence	Pressure Pillow	X	X	X		0.7
Snow Density and Depth	Radioisotope Profiler*	X	X	(Portable)		10.0 (4.0)
Snow Liquid Water	Microwave Profiler	X	X			2.0
Insolation	Sunshine Duration		X			0.5
Snowpack Characteristics	Monthly Snow and Air Surveys				X	
Snow Temp	Thermocouple	X				0.7
Soil Temp	Thermocouple	X				0.7
Selected MOS† Predictors		X				
Streamflow	Calibrated Stage Gages	X	X	Δ		0.5

*Wilderness Act will not exclude use.

ΔGages at all tributaries.

†Weather prediction technique: Model Output Statistics (see Chapter 6).

cheaper platforms or the use of one platform to serve several third order stations with ground to ground data transmittal between them might be preferable.

With regard to the Wilderness Act, efforts are currently underway (Sisk bill) to legitimatize reasonable data collection. In any event, at present, sensors such as the density profiler may be used at existing snow survey sites and correlations made with other stations.

Conclusions

The following are drawn from the results derived from this study.

1.   Energy Loss Mechanisms

The major energy loss mechanism is the spillage of water — a forced release of water when the power pool is full and inflows are greater than turbine capacity.

A major cause of spillage is the inability to predict short term, high inflow events with sufficient accuracy, such that storage space can be made available in anticipation of the event. If high inflow events can be predicted, spill reduction and the consequent benefits increase in a roughly linear fashion with anticipation time and with forecast accuracy (up to three to four weeks).

Benefit functions have been derived for Folsom, Shasta and Trinity Reservoirs of the Central Valley Project; for the main stem of the Columbia River and the lower Snake River; and for the large hydropower plants in the upper Missouri River Basin. Improved short term streamflow predictions can produce benefits of about one-half percent to one percent of annual generation for each day of high inflow anticipation. Three days of anticipation at Folsom with 80 percent accuracy will yield an additional 10.5 GWH of energy per year, an equivalent benefit of $52,500 at $5,000 per GWH. A rough extrapolation to all of Northern California (based on analyses of Shasta, Trinity, Folsom and Oroville) gives an annual benefit of 200 - 300 GWH.

Additional large benefits are possible if inflow forecasts are sufficiently accurate to permit reductions in the size of flood control reservations; this could be done for high confidence forcasts only. For Folsom an increase

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of approximately two percent of annual energy generation can be achieved per day of anticipation.

A second major cause of spillage is due to under-estimates of seasonal run-off, such that less than allowable releases are made early in the season. This type of loss mechanism can occur with very large reservoirs (power pool approximately equal to total seasonal run-off). The large reservoirs on the Missouri are in this category, but analyses indicate little likelihood of beneficially altering the release schedules of these reservoirs because of downstream flow constraints.

Better seasonal estimates can also serve to reduce flood reservations when these are determined (in part) by expected run-off for the remainder of the season.

2.   Role of Improved Information Systems

Hydropower output can be increased through use of information systems that provide increased anticipation times and accuracies for high inflow events. There are two basic anticipation mechanisms. The first is weather and climatic forecasting; current forecast methods limit the anticipation time for reasonably accurate forecasts to less than three days.

The second mechanism is hydrologic system lag time, i.e., the time between rainfall or snowmelt and inflow to the reservoir; this lag time is a function of the system topography and geometry, the value of the snowpack and ground hydrologic system state variables, and the locations of the reservoirs with respect to the watersheds. This lag is normally in the range of 0 - 5 days.

3.   Hydrologic System Modeling

A hydrologic model is required for the short term inflow forecasting process. The accuracies of existing models are reduced because they do not represent the snowpack as a complex, time-varying hydrologic system which interfaces with a ground hydrologic system. Snowpack parameters such as density and liquid water content profiles, which determine drainage rates during the all-important melt season, are not utilized. In addition, although the better models include options for sub-basin partitioning and snowpack

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energy budget calculations, these options are rarely used for lack of sufficient data.

Current hydrologic models employ a relatively large number of parameters; the most sensitive of these simulate underground soil physics and are not amenable to sensing in the field. Those variables which are available for sensing and have high sensitivity values (ratio of percent change in run-off to percent change in variable) are, in approximate order of importance:

1) Precipitation amount

2) Upper Zone Soil Moisture content

3) Snowpack area, Water Equivalence

4) Insolation, Air Temperature, Wind Speed.

Most models do not obtain the data for item 4). Water equivalence of the snowpack is currently sampled by pressure pillows (and manual surveys) and is sometimes used in estimating total seasonal runoff. Other aspects of the snowpack structure which are vital to daily inflow forecasts and to time lag estimates between precipitation and inflow can be sensed with radio isotope/ microwave profilers, but these are not in operational use. Snow depth, density profile and liquid water content profile, which are strong indicators of pack maturity, can be sensed with these devices. These snowpack parameters rank in importance between items 1) and 2) during the snowmelt season.

Because many variables contribute to the overall accuracy (variance) of the model, a large improvement in any one variable will not reduce total variance appreciably.

Short term streamflow predictions on the basis of hydromet modeling of watershed runoff phenomena are used only by a few major hydropower operators, but the use of such models is gradually being extended. Programs should be initiated to encourage and support the extension of information systems using this technology to a broader sector of the hydropower industry.

4.   Synoptic Models

A number of investigators have developed relationships between fraction of total seasonal runoff and the fraction of basin area covered by the

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snowpack, based primarily on LANDSAT MSS data. Good correlations have been obtained for selected watersheds for one or two snow seasons. If a high degree of correlation can be obtained over a number of years of observations, the relationships would help improve refill strategies for reservoirs, particularly those that derive a major fraction of season inflow from the snowpack. Data gathering for this purpose has been impaired by lack of cloud-free viewing time over major watersheds in the Pacific Northwest, which is the major producer of hydropower in the United States.

5.   Weather Forecasting

Weather forecasting shows rapidly decreasing accuracy with time and quantity of precipitation; accuracy levels seldom exceed 30 percent, and predictions generally are limited to 2 - 3 days. Since high inflow events must be forecast with reasonable accuracy for improved hydropower benefits, both of these characteristics reduce its effectiveness. Use of historical records for local weather patterns (the "MOS" technique) can yield improvements, both with regard to precipitation probability and amount, and to factors such as wind and air temperature. The MOS technique is presently being tested for use in the Columbia River Basin. The use of remote sensors for enhancing weather predictions for hydropower uses does not appear promising for the near term.

6.   Remote Sensors

The only significant and proven remote application of air/spaceborne sensors to date is the use of visible and IR photoimaging for the sensing of snowpack area. These sensors are operationally limited by cloud and forest cover and by the requirement for sufficiently low altitude for good imaging. The latter results in low frequency satellite coverage, which exacerbates the cloud problem. Nevertheless, MSS sensors are useful for updating snowpack areal extent when such sensing is feasible.

The extent of forest cover and other hydrologic model parameters can be sensed by these sensors but there is little cost incentive for such sensing because most such parameters are relatively unchanging. IR sensors can detect meltwater on snow, but such meltwater is a diurnal occurence and no particular indicator of snowpack maturity.

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Remote microwave sensors are in the initial stages of some promising developments, but considerable theoretical and developmental efforts are required to make these sensors operationally useful. Both passive and active sensors can be potentially effective in the frequency bands less than 10 GHZ, although dense foilage will always present problems; passive microwave at orbital altitudes suffers from poor resolution and low signal power.

Basic difficulties for both types of microwave sensing arise from the complex nature of the snowpack and its interface with the ground hydrologic system, and the extreme non-uniform conditions over the watershed. It may be possible to develop simple, inexpensive reflectors placed at various heights above the ground, and distributed at key watershed locations, to enhance the effectiveness of active air/spaceborne microwave "probes."

With a few exceptions, there is a lack of quantitative data, either from analytical or experimental studies, to perform a detailed assessment of the feasibility of measuring hydrometeorologic model variables with air/spaceborne microwave sensors.

7.   Information System Concept for the Near Term (to 1985)

Based on a review of sensor requirements and state of the art and near term capabilities, it appears that improvements in information systems for hydropower operations will depend primarily on more extensive use of ground based sensors in conjunction with better ground and snowpack hydrologic models, MOS weather forecast techniques, and satellite data collection systems. The Columbia River Operation Hydromet Management System (CROHMS) incorporates many of these elements, or is planning to do so. The basic hydrologic model of the SSARR type contains the requisite snowmelt and split watershed options. A denser sensor net and correlation of field data with that obtained from heavily instrumented reference stations in the area would support such options and would reduce sampling errors, which are a major error source for these models. In addition, recent ground sensor developments, such as the microwave liquid water profiler and the radio-isotope density gage, make possible a much more adequate treatment of snowpack structure and maturity than heretofore. MSS supplied snowpack areal extent information is desirable, updated as frequently as is feasible. MOS weather forecast techniques would tend to increase high inflow anticipation.

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Recommendations

In addition to on-going activities discussed above, the following recommendations are made for new analyses and R&D program activities.

1) Reformulate watershed runoff models to include snowpack parameters such as density and water content profiles and water equivalence. Adequately subdivide a heterogeneous watershed into subregions.

2) Initiate demonstration tests of selected air/spaceborne microwave sensors for measuring snowpack state conditions including passive "reflector" aids.

3) Develop reliable, low cost ground based sensors for measurement of precipitation and soil moisture.

4) Expand the use of satellite data relay systems techniques for selected projects and for specific regions.

5) Determine the effectiveness of MOS outputs for snowmelt prediction.

6) Establish through analyses the inflow forecast reliability necessary for the hydropower operator to use such forecasts regularly in his determination of reservoir release policy.

7) Determine acceptable forecast reliabilities for reducing reservoir flood control space in response to these forecasts.

8) Initiate a nationwide program for the use of advanced hydromet information systems for control of relatively short term high inflow events. Specifically:

   a. Extend survey of hydropower installations to determine types of hydromet information systems required, and the number of installations requiring each type; the analysis methodology outlined on page 2 is well suited for this purpose.

   b. Initiate and support a program to disseminate the modeling, instrumentation, and computer-communications system technology to the user community defined in (a).

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c. Encourage and support the development of efficient, inexpensive instrumentation to monitor snowpack conditions.

d. Encourage and support the development of more effective hydromet modeling technique for the user community identified in (a). These are the prime elements in predicting dynamic inflow events.

e. Prepare and disseminate to the user community planning implementation guidelines manuals for hydromet information systems including data acquisition, transmission and processing.

1. INTRODUCTION

This report presents the results and supporting analysis of a study of information systems for hydropower operations. The analysis was performed for the Office of Energy Programs, National Aeronautics and Space Administration, under RTOP 777-30-01.

General Objective

The general objective of the study was to analyze the operations of hydropower systems, with emphasis on water resource management, to determine how aerospace derived information system technologies can effectively increase energy output. Better utilization of water resources was sought through more accurate reservoir inflow forecasting based on use of hydrometeorologic information systems with new or improved sensors, satellite data relay systems, and use of optimal scheduling techniques for water release.

Approach

The principal guideline for the study approach was to develop a qualitative and quantitative understanding of the interrelations between hydropower operations and the supporting hydrometeorologic information systems. To accomplish this, specific mechanisms for improving energy output were determined, primarily the use of more timely and accurate inflow information to reduce spillage due to short term high inflow events. (This type of spillage is a dominant loss factor for a major class of hydropower installations.)

The present study differs significantly from the prior studies both in the methods for reducing spillage, and consequently, in the analysis approach. Prior studies have concentrated primarily on the seasonal aspects of spillage, and cost benefits were derived on the basis of percentage reductions in total seasonal spillage. Specific mechanisms by which improved information systems could bring about these reductions were not defined; however, improved predictions of long term, seasonal precipitation are implied. Improvements in such predictions are quite speculative at present, and detailed, quantitative analyses of advanced information systems for this purpose are somewhat premature. This in fact has been the dilemma encountered in prior studies.

The present study established at an early stage in the analysis that, for a large number of major reservoirs, spillage is a dynamic, short term phenomenon attributable to unanticipated high inflow events. This type of spillage can be reduced in direct proportion to the number of days of anticipation (0 to 20 days) and to the accuracy of the inflow forecast. By defining the problems in these terms, specific methods for reducing spillage could be identified and their potential assessed. Basically, two techniques are useful for short term inflow prediction: the first is weather forecasting, and the second, use of empirical modeling techniques to simulate runoff from the snowpack and ground hydrologic system. Both techniques provide estimates of the amount and time of arrival of inflow (in most watersheds, moisture input to the snowpack/ground hydrologic system requires several days to reach the reservoir). Both processes can be modeled. Further, we can establish the sensitivities of the model outputs to errors in the measured variables. These sensitivities form the basis for sensor and overall information system requirements: which variables must be measured, with what accuracies and how frequently; what is the desired density of the sensor network; how quickly must the inflow predictions be disseminated to the hydropower operators; and, what modifications to the models would improve the predictions. Finally, having determined sensor requirements, sensor capabilities can be compared to requirements, and a sensor set selected that best meets these requirements.

This approach has been used in the present study to define in a quantitative manner the spillage loss mechanisms and the benefits that can reasonably be expected from improved information/sensor systems, and to provide guidance for sensor R&D programs and the supporting data acquisition, transmission, processing and dissemination subsystem developments. The analysis activities were supplemented by many contacts with industry and government hydropower operators, who provided much useful data as well as the basic computerized hydrometeorological models; the latter are particularly valuable because they are based on actual operational policies and constraints.

Chapter 2 describes the study approach, and outlines the specific steps followed in the analysis. Prior studies are reviewed briefly in Chapter 3.

Chapter 4 analyzes and quantifies the characteristics of hydropower operations. Specific mechanisms for improving energy output are determined, principally the reduction of spillage through use of more timely and accurate short term (0 - 7 days) inflow information. The models used in predicting inflows are then examined in detail in Chapters 5, 6 and 7 to determine the sensitivity of inflow prediction accuracy and associated lag times to the many variables employed in the models; the results are used to develop general and specific sensor requirements. A survey of sensor capabilities is presented in Chapter 8, and an information system concept outlined in Chapter 9 based on a comparison of sensor requirements and capabilities. Conclusions and recommendations are given in Chapters 10 and 11.

Supporting information is given in appendices in the main report. A comprehensive review of the related literature is presented in Appendix D.

2. STUDY APPROACH

The principal guideline for the study approach was to develop a qualitative and quantitative understanding of the interrelations between hydropower operations and the supporting hydrometeorologic information systems. To accomplish this, specific mechanisms for improving energy output were determined, primarily the use of more timely and accurate inflow information to reduce spillage due to short term high inflow events. (This type of spillage is a dominant loss factor for a major class of hydropower installations.)

The present study differs significantly from the prior studies both in the methods for reducing spillage, and consequently, in the analysis approach. Prior studies have concentrated primarily on the seasonal aspects of spillage; percentage reductions in total seasonal spillage were assumed, and cost benefits derived on the basis of these reductions. Specific mechanisms by which improved information systems could bring about these reductions were not defined, however, improved predictions of long term, seasonal precipitation are implied. Improvements in such predictions are quite speculative at present, and detailed, quantitative analyses of advanced information systems for this purpose are somewhat premature. This in fact has been the dilemma encountered in prior studies.

The present study established at an early stage in the analysis that, for a large number of major reservoirs, spillage is a dynamic, short term phenomenon attributable to unanticipated high inflow events. This type of spillage can be reduced in direct proportion to the number of days of anticipation (0 to 20 days) and to the accuracy of the inflow forecast. By defining the problems in these terms, specific methods for reducing spillage could be identified and their potential assessed. Basically, two techniques are useful for short term inflow prediction: the first is weather forecasting, and the second, use of empirical modeling techniques to simulate runoff from the snowpack and ground hydrologic system. Both techniques provide estimates of the amount and time of arrival of inflow (in most watersheds, moisture input to the snowpack/ ground hydrologic system requires several days to reach the reservoir). Both processes can be modeled. Further, we can establish the sensitivities of the model outputs to errors in the measured variables. These sensitivities form the basis for sensor and overall information system requirements:

which variables must be measured, with what accuracies and how frequently; what is the desired density of the sensor network; how quickly must the inflow predictions be disseminated to the hydropower operators; and, what modifications to the models would improve the predictions. Finally, having determined sensor requirements, sensor capabilities can be compared to requirements, and a sensor set selected that best meets these requirements.

This approach has been used in the present study to define in a quantitative manner the spillage loss mechanisms and the benefits that can reasonably be expected from improved information/sensor systems, and to provide guidance for sensor R&D programs and the supporting data acquisition, transmission, processing and dissemination subsystem developments. The analysis activities were supplemented by many contacts with industry and government hydropower operators, who provided much useful data as well as the basic computerized hydrometeorological models; the latter are particularly valuable because they are based on actual operational policies and constraints.

For convenience in presenting the results of the work, the analysis tasks are described below:

1) Characterize hydropower operations relating to energy production. (Hydropower generation is governed by a variety of water release constraints, and a high degree of variability in the water inflow to the reservoir.)

2) Identify mechanisms responsible for less-than-optimum production, principally spillage resulting from lack of timely and accurate inflow information. Estimate benefits derivable from the forecast of high inflow events, and resulting reduction in spillage. (The reduction in spillage for a major class of reservoirs is shown to be related to the number of days of anticipation of high inflow events, and to the accuracy of inflow forecasts.)

3) Identify the principal processes that contain information about the time of arrival and magnitude of high inflow events, primarily the meteorologic and watershed ground and snowmelt runoff processes. Acquire models of the hydrometeorologic processes (weather forecast and ground/snow hydrologic models) from industry and government sources.

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4) Determine the sensitivities of the hydrometeorologic models to uncertainties or errors in the model variables, i.e., influence of sensor system accuracy on the accuracy of predicted inflow magnitude and arrival time.

5) Establish information/sensor system requirements to achieve a desired accuracy in inflow prediction.

6) Survey the capabilities of state of the art and advanced information/ sensor system elements to determine feasible concepts for improved information systems.

7) Develop an improved information system concept.

This approach to the analysis of hydropower systems is reflected in the following discussion.

3. REVIEW AND CRITIQUE OF PRIOR STUDIES

Many studies over the past 8 - 9 years have addressed the potential for improving hydropower operations through the use of advanced information systems, based principally on the use of air/spaceborne sensors to improve the accuracy of predicting reservoir inflows. These studies generally were designed to provide guidance and support for remote sensor R&D programs by assessing the potential cost/benefits of applying these sensors to hydropower operations.

The principal loss in hydropower operations identified by the prior studies was spillage, i.e., release of water over spillways to avoid encroach- ment of flood reservations.[1] In a majority of studies historic reservoir release records were obtained on one or more major hydropower systems, and the total spillage summed for the season. The resulting loss of water was used as the basis for estimating the dollar benefits that could be realized if spillage were eliminated.

This general approach provides an upper bound estimate on potential benefits, assuming that mechanisms exist for reducing spillage. The usual mechanism put forth was an improvement in the accuracy of the prediction of total seasonal precipitation. Such improvements are quite speculative at present, and benefits derived on this basis tend to be over-estimated.

The results of six key cost/benefits studies are summarized in Table 1; these studies cover nearly a decade of activity in this area since the PRC effort was initiated in 1967. For each study the table gives the estimated annual benefits for reducing or eliminating spillage; the basis for the estimate, the analysis technique; the extension of the case study results (Grand Coulee, Oroville, etc.), to the entire United States; and the extent to which forecasting techniques were analyzed, if at all.

As an example, the ECON 1974-75 studies were based on analyses of Oroville operations on the Feather River. The early study (1974) simply assumed that the flood reservation could be reduced 20% through improved forecasting. Since the total flood reservation can reach 750,000 AF

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1. That fraction of the reservoir storage volume that must be reserved for a flood event.

Table 3-1. Review of C/B Studies (Satellite Based Systems).

STUDY	ANNUAL BENEFITS (MILLION $)		BASIS	ANALYSIS TECHNIQUE	EXTENSION TO U.S.
PRC-1969 (GRAND COULEE)	HYDROPOWER FLOOD IRRIGATION (U.S.)	94 305 282 688	PERFECT SEASONAL INFO, NO HEDGE, OPTIMAL DRAWDOWN & REFILL, PERFECT KNOWLEDGE OF IRRI-GATION DEMAND, RIVER LEVEL REDUCED TO MINIMIZE FLOOD-ING.	UPPER BOUND ESTIMATES	TYPE AND SIZE OF RESERVOIR, IRRIGATION ACREAGE, FLOOD LOSSES IN U.S.
EARTH SAT CORP - 1974 (HUNGRY HORSE)	HYDROPOWER (WESTERN STATES)	10 - 28	PARAMETRIC VARIA-TION OF SEASONAL FORECAST ACCURACY	SIMPLIFIED SIMULATION OF DRAW & REFILL	RATIOED BY KWHRS
ECON - 1974 (OROVILLE)	HYDROPOWER IRRIGATION (WESTERN STATES)	42.0 8.6 50.6	ASSUMED A 20% RE-DUCTION IN FLOOD RESERVATION.	UPPER BOUND ESTIMATES	RATIOED BY KWHRS
MICH (1974) (PALISADES)	IRRIGATION (PALI)	.38-.76	PERFECT INFO FOR SHORT TERM (30 DAYS) AND LONG TERM.	SIMULATION MODEL (DAILY)	
*ECON (1975-1) (OROVILLE)	HYDROPOWER IRRIGATION	.6 2.2 2.8 (ORO) 19.2 (U.S.)	PARAMETRIC IMPROVE-MENTS IN SHORT TERM (30 DAY) FORE-CAST.	SIMULATION MODEL (WEEKLY)	ALL WATERSHEDS WITH 811 KAF, 200 MW, 1000 GWHR, LARGE SNOW PACK.
ECON (1975-2) (SHASTA, GRAND COULEE, HOOVER, + 6 WESTERN RESERVOIRS)	HYDROPOWER IRRIGATION FLOOD	.65 .34 --- .99	FRACTION OF UPPER BOUND ESTIMATES.	UPPER BOUND ESTIMATES	(AS IN 1975-1). NOTE: SHASTA DOES NOT MEET CRITERIA, BUT CONTRIBUTES 33% OF BENEFITS.

*ALSO CONCLUDED THAT IMPROVED MEASUREMENT OF SNOW PACK DOES NOT IMPROVE FORECASTING SIGNIFICANTLY.

(over one-third of the active storage volume of the reservoir), projected benefits due to a 20% reduction in the reservation are very substantial. No specific mechanisms were identified or hypothesized for achieving the improvement in forecasting. In actuality, the flood reservation at Oroville is based on accommodating a "maximum" storm event, 9 inches of rain in approximately 4 days. To reduce the flood reservation, it would be necessary to establish with a high degree of confidence, that a major storm could be forecasted both as to the time of occurrence and amount of precipitation. Weather forecasting techniques cannot achieve the necessary accuracies since forecast scores decrease rapidly beyond the first 24 to 36 hours, and decrease with increasing amounts of precipitation. Hence, the ECON-1974 benefits assumptions are optimistic. Extrapolating the benefits based on the Oroville case study to a large number of other hydropower systems is unrealistic.

The ECON 1975-1 study, also based on Oroville, is a significant improvement over prior analyses in that the benefits are related to forecast period, i.e., days of anticipation, and accuracy. These results provide a clue as to the role of short term inflow forecasting in hydropower operations. Unfortunately the investigators did not extend this analysis to examine short term inflow forecast techniques, which involve streamflow synthesis and weather forecasting, both of which can provide a limited number of days of anticipation. The ECON 1975-1 study went on to estimate benefits based on perfect information, and extrapolated the results to other hydropower plants meeting certain criteria related to storage and generating capacity, and fraction of inflow derived from snowmelt. The resulting total estimate of benefits for all watersheds is questionable.

The ECON 1975-1 report also concluded that more accurate measurements of snowpack water content would not increase hydropower output at Oroville because such improvements would not lead to better estimates of total remaining inflow for the season, i.e., could not contribute to perfect long term inflow predictability, which they had previously identified as the only means for improving hydropower output. This conclusion is inappropriate for several reasons; First, hydropower output can be enhanced if short-term forecasting (2-20 days) can be improved, since, as will be shown, measurements of the snowpack are vital to short term, dynamic forecasting. Secondly, other investigators have shown some correlation between the areal

extent of snowcover and percent of the remaining seasonal inflow; if these correlations can be established with reasonable confidence for given river basins, the information might be used to reduce flood reservations, although an adequate data base is not currently available. Finally, major hydropower systems in the Pacific Northwest have relatively heavier snowpacks, which places greater emphasis on accurate knowledge of the snowpack; the general applicability of the conclusion is therefore questionable.

The ECON 1975-2 study perpetuates the "upper bound" approach to benefits analysis used in prior studies with the same assumptions and conclusions. A more sophisticated attempt was made to extrapolate the benefits estimates to major reservoirs in the Western States, but the approach did not address the dynamic, short term nature of spillage, nor the capabilities and limitations of information systems that must be relied upon for high inflow anticipation.

In summary, prior studies have consistently based benefits estimates on an assumed percent reduction in total spillage over a season; the levels of reductions were arbitrarily chosen, and not related to an assessment or analysis of information system capabilities or constraints. The dynamic, short term nature of spillage, which is usually caused by unanticipated high inflow events, was not fully represented in the analyses, although the ECON 1975-1 study developed a relation between benefits due to spillage reduction and days of forecast with various degrees of forecast accuracy. As a result of the over emphasis on seasonal forecasting, information systems techniques providing short term inflow forecasts were not identified, and hence, not properly evaluated; further, the ground and snow hydrologic system models, and weather forecast techniques upon which such information systems must be based, were not identified nor analyzed except by PRC, however, PRC did not relate inflow lag times and weather forecastability to spillage reduction potential. Admittedly, information systems cannot hope to achieve perfect forecastability in the foreseeable future, but with improved hydrometeorologic models, better anticipation of high inflow events is achievable; benefits due to spillage reduction through short term forecasting will not be large compared to the upper bound seasonal limits, but the potential gains are not insignificant.

An outcome of prior studies has been the failure to provide proper guidance to information systems R&D programs, particularly those dealing with air/spaceborne sensors. Too few analytical studies of remote sensor applications to hydrometeorological information systems are available, particularly those that address the difficulties of measuring and interpreting key variables for complex snow and ground hydrologic systems in non-uniform mountainous terrain. Results obtained over level, uniform topography have been too easily extrapolated to the far more difficult hydrologic systems associated with hydropower operations. Future studies must be oriented to address these factors.

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12.   Simmons, J. W., and R. Ambaruch, "Application of Remote Sensing to Hydrology." IBM Federal Systems Division 73-W-00387. September 1973.

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4. ANALYSIS OF HYDROPOWER OPERATIONS

4.1 Objective and Scope

The purpose of this analysis was to determine the extent to which more complete and timely watershed runoff and streamflow information than currently available, such as might be obtained with remote sensors and advanced information system technology, can improve hydropower productivity. It was also desired to determine the necessary characteristics of such information and its utilization for efficient system operation. An underlying assumption of the analysis is that markets for increased energy generation during both peak and offpeak hours exist and that transmission to these markets is feasible.

It is not within the scope of the analysis to consider modifying the system constraints, or increasing the number of turbo-generators or improving their performance, or increasing coordination of hydropower and thermal plants.

4.2 Operational Characteristics

Typical hydropower system requirements, operating procedures, constraints, and data sources, as they are relevant to an increase in hydropower generated energy through the application of improved runoff and streamflow information, are discussed in this section. In particular, those practices and procedures which relate to energy losses in the conversion of the potential energy of the streamflow to hydroelectric energy are considered in detail.

Types of Systems

Major U.S. hydropower facilities are listed and characterized as to location, ownership and installed capacity in Appendix B. The larger systems are generally Federally owned and multiple purpose. These purposes will include one or more of flood control, navigation, recreation, and irrigation and other water supply functions. As a general rule these several purposes will constrain hydropower productivity; however, the flood control objective, in its reservation of reservoir storage space for the containment of possible flood conditions, offers an opportunity for a substantial gain in hydropower benefits, with no increase in flooding risk, through improved streamflow forecasting. These gains will be discussed in subsequent sections.

The largest hydropower concentrations are in the western United States and almost one half of the total national capacity is in the Pacific Northwest. The western facilities are characterized by snowmelt serving as a major contributor to watershed runoff and streamflow. It is the dominant contributor in the Northwest. Information relative to the snowpack and the details of its melting is therefore particularly important. In addition, the storage of potential runoff on the ground offers an opportunity for forecasting streamflow which appears quite promising.

Many of the facilities are run of the river plants, that is, with insignificant storage space in conjunction with the hydropower generators, and therefore apparently offer no opportunity to use improved streamflow information if it were available. In other words, these plants generate on an "as it comes" basis, and streamflow prediction is of no help in increasing hydropower production. However, in an important number of such plants the streamflow is at least partly regulated by discharge from an upstream storage reservoir. Consequently, the productivity of the run of the river plant can possibly be improved through better information as to inflows into the upstream reservoir and judicious management of releases from it.

Within any particular area having a given set of hydro-meteorological conditions, the most important hydropower descriptors are storage space in the power pool and installed capacity. These can be used to extend approximately the results of a detailed analysis of one hydropower system to other systems in the same general area. .

Operational Requirements

In addition to the usual physical, contractual, institutional, and legal constraints, and those constraints corresponding to the several system purposes, an important constraint which is often formally unstated is that of ensuring continuing operations for an indefinite period. In the face of the stochastic characteristics of precipitation, snowmelt, and streamflow a system operator will be cautious of the reservoir releases he makes, operating relatively closely to the top of the reservoir power pool, unless he is reasonably certain of an ample inflow in the near future. Many hydropower systems, particularly in the West, depend on a high inflow season to fill their reservoirs and release a portion of their contents the remainder of

the water year to meet requirements at those times. Usually, it is hydropower generation which is optimized in the system operation, as it is often the single objective for which appreciable benefits can be obtained from a real time optimization. Improved information as to future inflows may thus encourage a release of additional water through the turbo-generators at such times as to increase hydropower production.

Hydropower system releases should be determined at least on an hourly basis to conform with the normal variability in power demand, particularly when the hydropower system is operating in conjunction with thermal plants that are supplying overall system base load. Since reservoir inflows and requirements are subject to seasonal cycling, a preferred method of operation is to examine and optimize a weekly or monthly model of the system over a year (with updating every week or month), use its outputs for a daily model, and finally proceed to an hourly model. The weekly and monthly predicted inflows are for the most part statistical and tentative, particularly for the later time periods. However, when snowpack is a major source of inflow a greater predictability is possible, and updating as soon as better information is available will enhance the utility of the longer term model and system optimization over the whole year.

The present trend, at least for large multifacility systems, is to centralize, automate, and computerize the system operation. However, monitoring by skilled personnel is always necessary, and reservoir releases can only proceed after approval by the operators. For the most part, basic inflow data is collected and entered via telephone into off-line data storage. The present degree of centralization and automation is dependent to a large extent on the availability of funds for this purpose and the particular configuration of the system; in any case, for the most part, management is receptive to technologies which can be shown to be advantageous.

It is important to note the procedures relating to the flood control function and the spilling of water, that is, the bypassing of the turbines and release of water over the spillways. Figures 4-1 and 4-2 for Folsom Dam and Reservoir, with inflows from headwaters on the western slopes of the Sierras, are typical. Figure 4-1 indicates the required flood control reservations which vary with calendar time and average precipitation over the
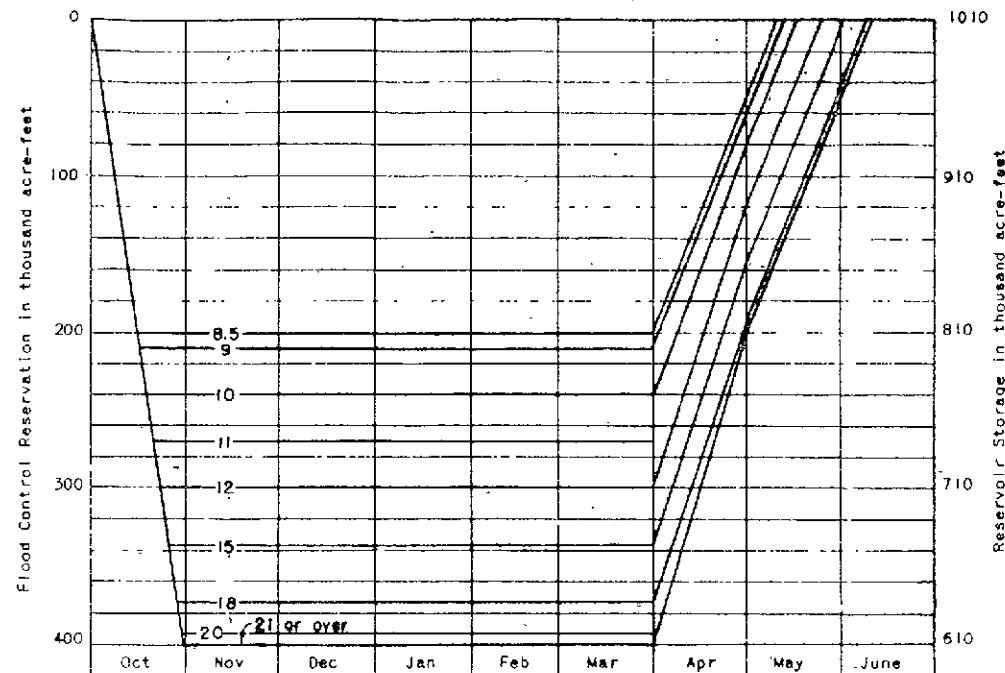
TABULATION OF RESERVATION VALUES

Parameter in inches	Reservation prior to 1 April	Reservation on 1 May
8.5	200	50
9	210	60
10	240	80
11	270	
12	300	120
15	336	156
18	372	192
20	392	
21	400	200

1. All interpolations are linear.

2. Reservations for any given parameter after 1 May decrease 5000 acre-feet per day.

USE OF DIAGRAM

1. Folsom Dam will be operated for flood control in accordance with this storage reservation diagram and the accompanying emergency release diagram, File No. AM-1-26-585. Under ordinary flood conditions, flood releases will be made in accordance with the storage reservation diagram. Under extraordinary flood conditions, releases will be made in accordance with the emergency release diagram. Whenever the pool level is above elevation 466 (gross pool) or when the pool level is above elevation 448 and is rising at a rate in excess of one foot per hour, the requirements of the emergency release diagram should be evaluated. Reservoir releases shall be made in accordance with the diagram requiring greater releases.

2. Parameter values are average precipitation in inches over the tributary area during the preceding 60 days. Calculations of average precipitation shall be based on an area average mean seasonal precipitation of 52." inches. Parameter values shall be computed bihourly during storms whenever encroachment is impending.

3. Except when releases are governed by the emergency release diagram, all storage in excess of that indicated by this diagram shall be released as rapidly as possible subject to the following conditions:

   a. That prior to completion of construction of the American River levee authorized in the Flood Control Act approved 3 September 1954, outflows at the tail water of Nimbus Dam do not exceed (1) 40,000 cfs or rate of inflow, whichever is greater, or (2) 70,000 cfs at any time.

   b. That after completion of construction of the American River levee authorized in the Flood Control Act approved 3 September 1954, outflows at the tail water of Nimbus Dam do not exceed 115,000 cfs.

   c. That outflows are not increased or decreased at a dangerously rapid rate.

Figure 4-1. Flood Control Storage Reservation Diagram

FOLSOM DAM AND RESERVOIR
American River, California

FLOOD CONTROL STORAGE RESERVATION DIAGRAM
Prepared Pursuant to Flood Control Regulations for Folsom Dam and Reservoir (33 CFR 208.87)

APPROVED: _____
Acting Commissioner of Reclamation

APPROVED: _____
Major General, Acting Chief of Engineers

Effective Date: 24 May 1956   File No.: AM-1-26-584

basin during the preceding 60 days. These reservations are calculated by using a Standard Project Flood based on a "reasonable combination" of the most severe meteorological and hydrologic conditions that can be considered representative of the particular region (Corps of Engineers) or a Regional Flood based on the maximum historical flood (TVA). The flood waves are then routed (tracing the downstream movement as a function of time) down-river through the reservoir, with the available storage space just equal to the reservation, and flood plain damage assessed. When the reservations are encroached, releases (major portion being spills) may be indicated, some minimal flood plain damage usually being caused. If pool level should get too high an emergency is declared and spilling proceeds in accordance with Figure 4-2. Substantial damage may then ensue, but there is no real alternative under those circumstances and possible dam rupture and catastrophic flooding must be avoided. The flood control function competes strongly with hydropower for available storage space. Thus in 1951, TVA spilled almost one million acre-feet of water to obtain flood control storage space. This same water, if retained, could have generated 560 million kilowatt-hours of electricity. Of course, spills may be made when streamflow is not in flood condition but only relatively high, if encroachment of the reservation is threatened. This could occur through inaccurate release schedulings in the previous periods, for example.

Pumped Storage Systems

There has been considerable recent activity towards the development and construction of large pumped storage systems. These are often combined with conventional hydroelectric systems or with large thermal plants. However, their purpose is never to add to the available supply of energy except in a purely local way. In a pumped storage system stored water which has been pumped from a lower level is available for release through turbo-generators to generate energy. But energy is always lost in the process; for every two kwh generated, approximately three kwh are required for pumping. That is, a well designed, large modern plant is about 67% efficient. In most cases the pumped storage developments utilize reversible pumping-generating units, although some high head projects may use separate pumps and even motors.

Their justification lies in one or all of the following reasons:

a. Off-peak energy is used for the pumping operation whereas the generated energy is utilized during peak load hours.

b. A relatively large amount of peaking capacity can be added for a short time to the available electrical plant, thus minimizing or delaying the addition of expensive conventional thermal or hydro-electric facilities.

c. At present, large thermal units, particularly nuclear, operate most efficiently at high plant factors. In other words, when these plants are operating at their maximum efficiency, excess energy may be available during off-peak hours. This energy may be used for pumped storage with possible overall economy.

d. Excess off-peak energy may also result from larger than antici-pated flows through the turbines of run-of-the-river and conven-tional storage plants.

Pumped storage developments may be useful for the objectives of this study in those situations in which a market for excess off-peak energy is not apparent or the off-peak rate is very low. This is because the use of better streamflow information to increase energy productivity will inevitably result in a large proportion of this increase being in off-peak hours. It is emphasized that this usefulness will be in terms of peak capacity and/or revenue gain rather than energy gain.

Hydropower Optimization

In actual operation of the storage reservoirs of a hydropower system one or both of the following problems are considered:

a. The scheduling problem —what releases should be made from which reservoirs to adequately conform to all constraints and requirements and remain in a position to continue operations with a high degree of probability. No optimization is necessarily implied.

b. The optimization problem — what is the best schedule that can reasonably be determined.

Both problems necessarily increase in complexity with size and number of objectives and requirements of the system. In the case of even moderately complex systems the problems tend to merge, as a practical matter, since many solution techniques yield an optimum with little more difficulty than for a non-optimum but feasible schedule. Decision models which address these problems are discussed in Appendix C. Some of the existing practices are indicated in this section.

Most single reservoir systems and portions of systems with non-integrated operations release water in accordance with fixed operating rules. The rules may be simple or complex according to whether they incorporate historical data only or also include dependence on such parameters as expected streamflow and anticipated demand. Operating by "rule curve" is, in effect, a form of scheduling which is generally satisfactory when sufficient historical data and sufficient flexibility are used. Rule curves are usually generated through multiple run simulation studies. Release policies are formulated so as to remain in a region defined by the rule curves although violations in specific situations may be authorized. Typically, a rule curve indicates acceptable values of end-of-period reservoir storage as a function of time over a time span of a year. The curve is usually defined at monthly intervals and straight lines drawn between the data points. An upper envelope is given by the flood control reservation variation with time (if there is no flood control function the physical maximum storage) and this envelope is generally variable with antecedent precipitation in actual operation. The lower envelope is often an energy curve obtained from simulation runs and defining the least acceptable reservoir storage which will guarantee meeting the firm energy and power commitments as well as other constraints for a hydrology no worse than any that occurred historically. In some cases the energy curve is made variable to reflect advantageous hydrologies. A typical rule curve is shown by Figure 4-3.

Various types of optimization models and procedures are used by the larger systems to determine their reservoir releases, and hydropower systems require release decisions to at least an hourly basis. These determinations can be difficult and lengthy and each system has, in effect, developed its own optimization algorithm suited to its own needs and responsibilities. Figure 4-4 illustrates an optimiation model which is being developed for the Central

Corps of Engineers
U.S. Army
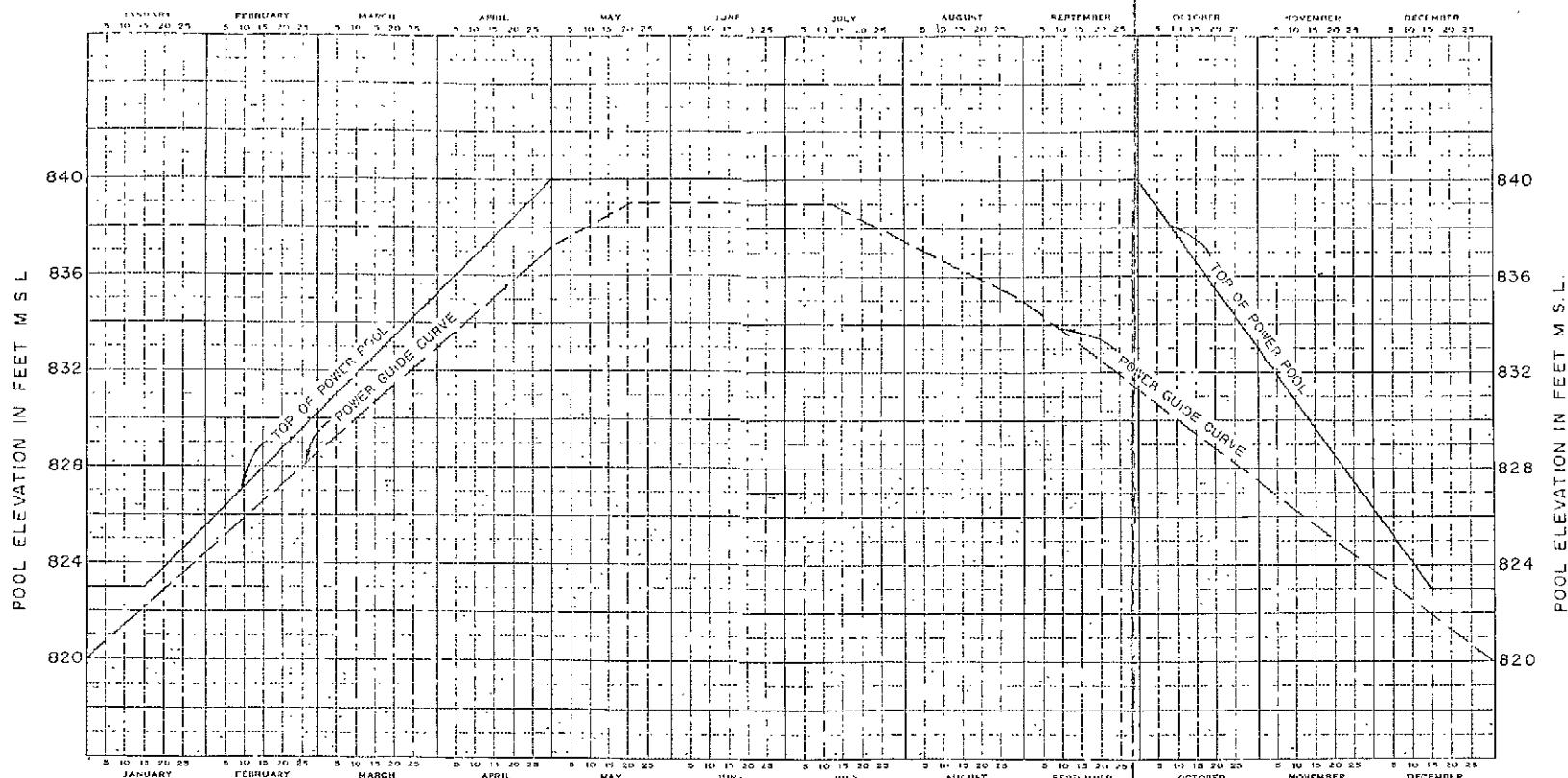
ALABAMA-COOSA BASIN

RESERVOIR REGULATION MANUAL

ALLATOONA RESERVOIR, ETOWAH RIVER, GA.

Figure 4-3. Guide Curve for Power
Operation.
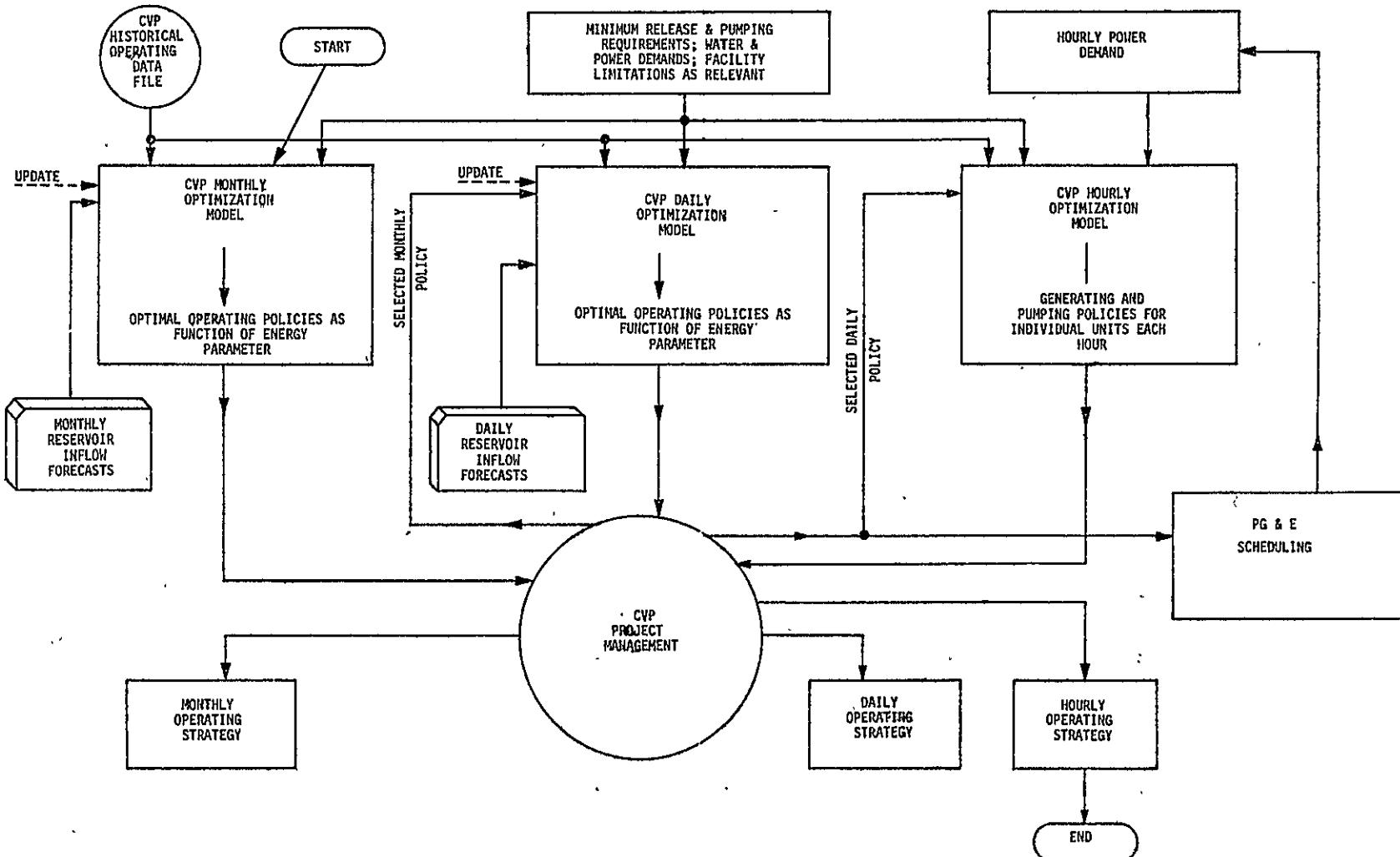
Figure 4-4. CVP System Optimization Model.

Valley Project of California (CVP) operated by the Brueau of Reclamation. The model is typical of the general structure and inputs required although the sub-model optimization algorithms (detail not shown) will differ. In the case of this particular system the hydropower generated is sold to the Pacific Gas and Electric Company (PG&E) from whom the desired hourly power profile is obtained. In other cases the profile is determined by agreement with cooperating utilities or independently in accordance with anticipated demand or market. Release policy updating is performed as frequently as the receipt of new information warrants, and the major effect of inaccurate forecast data is to increase the probability of spilling water in the future or to degrade the average head under which hydropower is generated over a period of time.

Data Sources

Streamflow forecasts are required by the hydropower system operators for their determination of optimal reservoir release policy. Both short and long period forecasts (for example, daily and weekly or monthly) are needed to minimize spilling and for optimization over the long term, and both types are susceptible to significant improvement through the accumulation and utilization of more accurate and timely data inputs. Such improvement will result in increased hydropower production provided that forecasts are sufficiently timely for effective anticipatory reservoir control actions to be possible.

The long period forecast is of particular consequence for seasonal inflow applications. The model used is necessarily statistical with the dependent variable the month by month (or week by week) reservoir inflows and the independent variables such quantities as snow water equivalent and various historical precipitation indices and runoffs. (In some basins a continually operating hydrologic model is combined with statistical precipitation estimates and discretized by days to produce long period forecasts.) Quite often more than one watershed is involved in consideration of the hydropower system, and some type of cross-correlation scheme is necessary for proper estimation of the parameters of the statistical models used for the watersheds since correlation effects are almost always present. Water content and depth of snow are often obtained through manually conducted snow surveys, once or twice a month during the season, at snow measurement sites or snow courses. Typical of depth variation is Figure 4-5 which gives snow depths at a site on
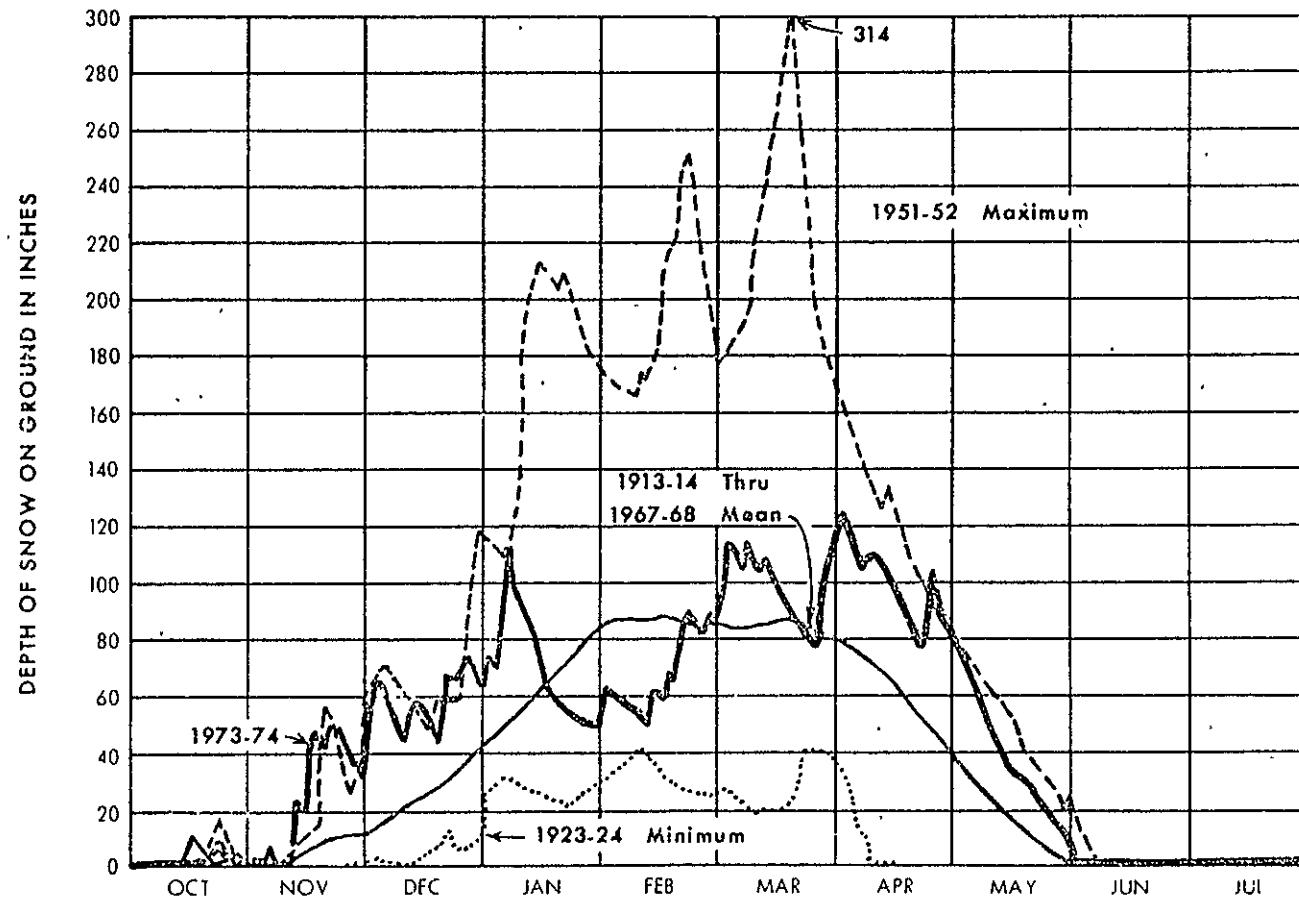
Figure 4-5. Norden — Depth of Snow on Ground 1973-1974.

the American River. Each course may be about 1000 ft long and contain 10-20 sampling points. A water equivalence index is calculated from these measurements which purports to represent the average over the effective areal extent of the snowpack, a quantity which is estimated from the snowpack boundary elevations but should consider only that portion of the snowpack susceptible to seasonal melting. At times, if a snow course is too hazardous, graduated markers may be read from low flying aircraft. Automatically reporting pressure "pillows" are frequently used to indicate water equivalence. Sources of error in this procedure relate to the estimation of the areal extent and to the use of the water equivalence index obtained from relatively few sample points in space and in time as representative of the areal average. The estimation of precipitation (rainfall) indices also suffers from this type of averaging error. (Gaging errors, which are functions of siting conditions and various meteorological characteristics, will contribute to the overall inaccuracy.)

Although the statistical model is not conducive to any fine grain estimation of streamflow, it can be very useful in predicting volume flows over some time period, information which may be useful in some cases (relatively large ratio of power pool variations to inflow during season) for the minimization of spilling. The model must be fitted to each watershed and its value depends on the accuracy of the fitted data, the existence of accurate historical data, and the variance of the data. No significant change in the watershed environment is, of course, assumed in applying the historical data.

Daily and hourly forecasts have sometimes used precipitation-runoff correlations derived in much the same way as are the longer term forecasts. However, because of the gross assumptions which were thus made and the resulting inaccuracies, the trend today is toward a direct consideration of the physical, hydrological, and meteorological parameters in the context of watershed models and with the use of high speed computers. In some instances, such as when reservoirs are located well downstream of river headwaters and tributaries or other regulated reservoirs, upstream flows can be gaged or are known and relatively simple routing procedures can translate these flows downstream in a very adequate manner.

At the present time there is not a standardized runoff estimation model. Each system manager and agency generates their own, although it would appear that a concentration on the general acceptance of some particular version would accelerate improvements of the runoff estimates. There is general agreement that remote sensing can contribute to better forecasting through an improvement in the determination of the areal extent of the snow-pack. In addition the use of an appropriate satellite as a repeater station could greatly enhance economy and reliability while permitting the utilization of a more dense network of automated ground stations than is now feasible. Usable data could be entered into runoff estimation models within hours and better forecasts made. Further, real time measurements of actual runoff, meteorological factors, and other parameters would enable frequent reinitialization and re-optimization of the models with resultant reductions in forecast errors.

To date, the Wilderness Act has not inhibited to a significant extent the collection of the necessary data, and it is not expected to do so in the near future.

Energy Loss Mechanisms

In normal operation of a hydropower system the energy potential of the stored and running water can be lost in one of two ways (other than evaporation) — an avoidable spilling of water (bypassing the turbines) or a failure to operate the plant at the highest average head.

Spilling will occur if an inflow is too large to pass through the turbines productively and there is no available space to store the water for later use (or if downstream demand requires an outflow greater than turbine capacity). With the spill, energy is irretrievably lost. If the inflow could be anticipated far enough in advance so that the reservoir could be operated at maximum turbine flow for a long enough period it might be possible to totally avoid spill; normally, the design and operation of reservoir and hydropower systems are such that greatly excessive streamflow cannot be completely stored nor passed through large enough penstocks and turbines, so that spill can only be minimized. The greater the time of anticipation of a high streamflow, the greater the hydropower savings. Thus, underestimations of streamflow may

cause spilling and energy loss, and partial corrections are possible through the use of updated information up to the time of high inflow. If, despite the underestimate, its use in system operation does not result in a spill, nothing is lost, under the generally reasonable assumption that the stored energy can be marketed just as profitably at a later time. A feasibility analysis should therefore consider a range of historical inflow data to investigate increase of benefits with better information. Figure 4-6 typifies reservoir operation during a rather wet year. Spills were made in November and December of 1973 and January, March, and April of 1974. Some of this spill could have been avoided with greater streamflow anticipation.

Generally, storage reservoirs are sized to spill safely — within downstream channel carrying capacity — during wet years. Ratios of this safe spill to maximum turbine flow can be as high as 10 to 15 to 1, and it can be seen that anticipation times in the order of weeks may be necessary to substantially reduce spilling, since during the wet or snowmelt season sustained high water will occur and available power storage space may be small. Such anticipation appears most likely in the case of snowpack and melt although any anticipation will produce some benefit. Equivalent long term prediction of rainstorm runoff does not appear too likely at this time; however, adequate rainfall and stream instrumentation and cloud surveillance may result in some appreciable benefits in such case. On the other hand, pondage plants may spill during normal years unless shorter terms (several days) forecasts are reasonably accurate.

Those systems and reservoirs subject to frequent spilling will also usually be supportive of a flood control function, and during the high water season a portion of physical reservoir capacity will be reserved for flood control. As previously discussed, the reserved space is allocated rather conservatively since there is usually imperfect information as to the quantity of storm runoff impending; this fact offers an additional possibility for an increase in hydropower production. If better precipitation and runoff forecasts can be made to the satisfaction of the responsible flood control agencies, it should be possible to decrease the allocated flood control reservations without any substantial increase in risk of flood damage. If this were done, an equivalent volume of water which would otherwise be spilled could be saved and, additionally, power releases would be made at an increased head with
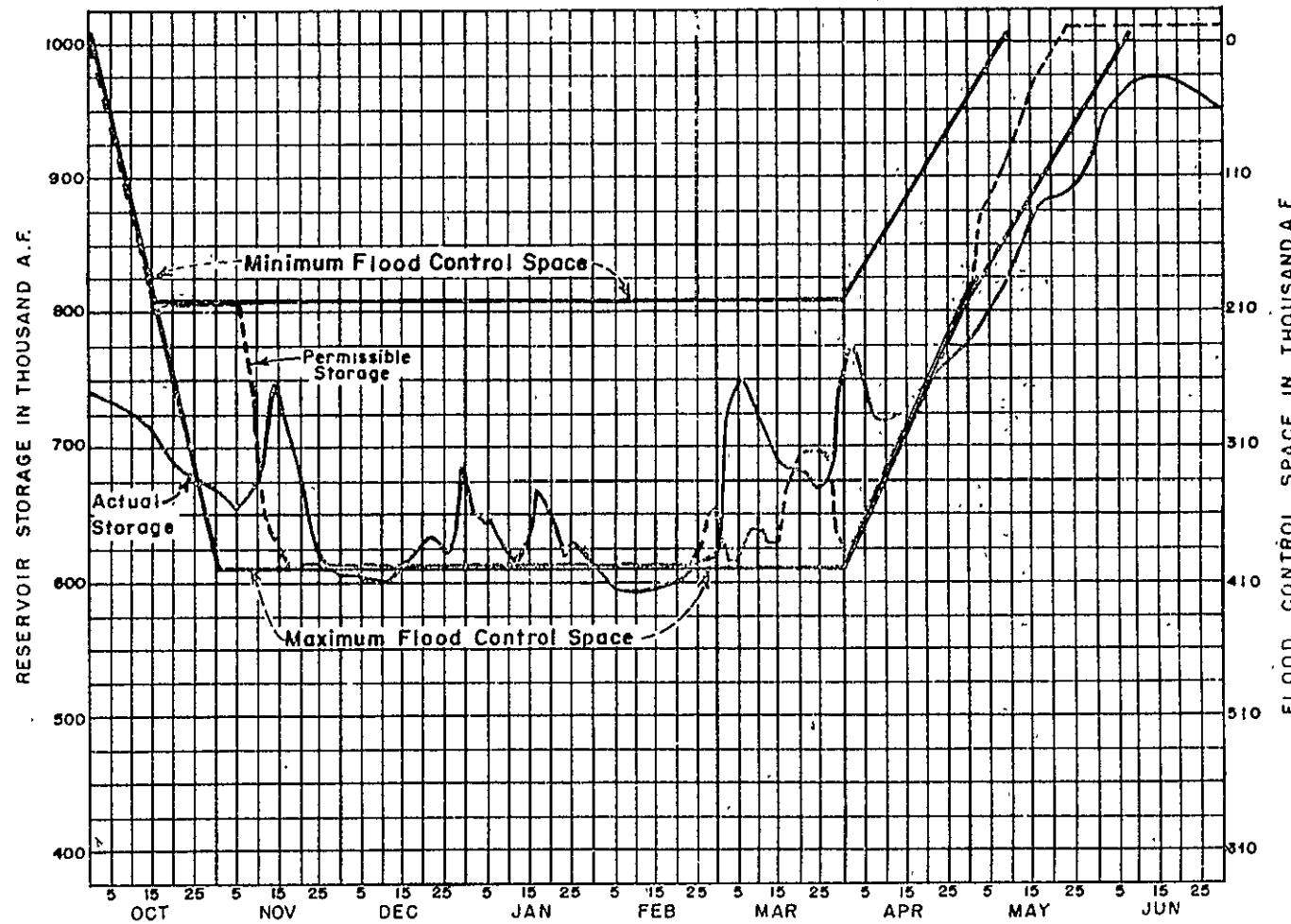
Figure 4-6. Operation of Folsom Lake for Flood Control 1973-74.

U.S. Department of the Interior, Bureau of Reclamation
Central Valley Project — California.

consequent increased energy production. In this case only a few days runoff anticipation beyond what is presently obtained would be sufficient to enable a large decrease in flood control regulation by spilling at the maximum safe rate for that time.

Overestimation of runoff and streamflow can also result in inefficient hydropower generation by premature release of water and operation at a lower head than necessary, as well as a risk of being unable to continue satisfactory operation. Operators generally bias against such risk. Severe overestimation may even cause unnecessary spilling for fear of potential encroachment of allowable maximum storage.

Spilling is relatively frequent for moderate sized and small reservoirs, particularly during the flood season, and constitutes the dominant energy loss mechanism in such cases. High inflow events, which can lead to spilling, are of relatively short duration (less than 2 weeks) and are characteristic of rainfall or a premature runoff of meltwater from a snowpack. Clearly, a realization of benefits through better streamflow forecasting necessitates a short term forecast of these high inflow events. Each day of anticipation of an event permits some partial control of the spill; however, the control is limited, consisting of additional releases through the turbines up to the maximum power release prior to the event.

4.3   Method of Analysis

Inasmuch as the larger hydropower systems are multiple purpose and the several objectives must be considered together, an accurate analysis requires consideration of the total system rather than isolated portions of it. Further, an operations optimization model is necessary to ensure that improved runoff estimated are most profitably utilized. In adition, a simulation of an actual operation entails a day by day consideration using updated inflow forecasts as they are available. The evaluation of an average annual hydropower benefit necessitates simulated operation of the system over a representative number of years, including both wet and dry seasons.

Since strict adherence to these requirements are very time consuming it was decided to perform a detailed analysis for one situation and to use the results as a basis for extrapolation to other situations as feasible. The immediate availability of watershed and optimization models suggested

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analysis of the Central Valley Project of California operated by the Bureau of Reclamation. A GSSS runoff model (Chapter 5) existed for the American River basin with inflow to Folsom Lake and power plant. Folsom is also representative of moderate sized reservoirs, and the runoff source is approximately 50% rain and 50% snow.

The total system was analyzed day by day over a 10-year period. The Central Valley Project is multi-basin, and inflows other than those into Folsom were used as listed in the historical records, without change; the Folsom historical inflows were parametrically varied to correspond to a varying number of days of anticipation of the inflow with varying forecast accuracies up to 100%. For each such forecast system-wide hydropower generation was optimized within system constraints and the Folsom generation (and spill) noted. Thus, hydropower sensitivity, in terms of energy benefits as a function of accuracy of inflow forecast, could be determined and combined with the watershed runoff sensitivities of Chapter 5 to yield the desired benefits as functions of the estimation accuracies of those watershed and climatic parameters which are amenable to sensing, particularly remote sensing.

Significant additional benefits are possible. If high inflows can be forecast with high probability (for example, by substantial improvement in near term forecasting of large storms or rapid snowmelt), it is possible that reservoir space now dedicated to flood control can be reduced and corresponding space added to the power pool. An estimate of the benefits that could be gained by such an action was made for Folsom Lake.

Folsom flood control regulations now provide that under non-emergency conditions a maximum release of 115,000 cfs (at the tailwater of Nimbus Dam) may be made with the rates of change within a two-hour period limited to 15,000 cfs when increasing flow and 10,000 cfs when decreasing flow. Using these values reductions in flood control space was made for a flood condition prediction capability of 1, 1.5, and 2 days, under the assumption that action within the above regulations would then take place to provide the same total flood control space as existed before the reductions. Thus, flood damage risk would not be materially increased.

Although watershed models for the other major facilities of the Central Valley Project were not available, inflow forecasts for these

facilities (Shasta and Trinity) were varied in similar fashion, but only for a representative month and assuming perfect accuracy, to permit an extrapolation of Folsom results to the entire system. The extrapolation was on the basis of comparative monthly benefits, and was considered reasonable since facility capacities and hydrologic variability and uncertainty are not dissimilar.

An order of magnitude extrapolation to all of the Northern California facilities was made on the basis of installed capacities and size of the power pool, since the hydrologies are roughly similar. Benefit estimates were also made for the facilities on the mainstream of the Columbia River using a historical data tape containing 7 years of daily information as to plant generation, inflow, power release, and spill for each plant. Although system constraints within an optimization procedure could not be applied, the data was considered adequate for an upper bound estimate of benefits obtainable for inflows forecast with 100% accuracy. The application of system constraints and forecast errors can only decrease these estimates. Additionally, historical operational data were used to obtain benefit estimates for the Upper Missouri Basin. In this case, and important winter release constraint clearly canceled virtually all benefits.

The combination of Folsom and American River basin runoff sensitivities produced hydropower benefits as functions of parameter measurement and prediction. Since spill is the dominant energy loss mechanism and only runoff underestimates result in spill, only those parameter errors which produced underestimates were considered. As noted in Chapter 5, a SSARR model snowmelt routine was used with the GSSS model, and the changes in snowmelt resulting from changes in the snowpack and climatic parameters were treated as if they were changes in precipitation inputs to the GSSS model.

4.4   Results

The results obtained in this hydropower system analysis have been necessarily limited by the time and resources at our disposal, and by the fact that an accurate determination of hydropower benefits that can be gained through better sensing methods and inflow information requires both an operational watershed runoff model and a short term hydropower optimization

model to effectively use the better information. Many large systems lack one or both of these models, although the trend is towards development of these operational aids.

Another problem is that virtually no watershed model includes, as a runoff influencing parameter, quantities such as snowpack liquid water content or mass per unit area which are important determinants of short term, high inflow events. The reason for this is that, heretofore, there was no reasonable way to obtain such data within the required time period.

Nevertheless, the results given in this section are considered representative of the maximum hydropower benefits that can be gained if 100% accurate forecasts over some period of time were available. The results also indicate the magnitudes of sensing and prediction errors that correspond to any specified deterioration in benefits, at least for those watershed and climatic parameters which define the watershed model used and are amenable to sensing.

4.4.1 Benefits vs. High Inflow Anticipation

American River/Folsom, Central Valley Project

A hydropower sensitivity analysis has been made for Folsom and Nimbus hydropower plants, a part of the CVP system which is schematically shown as Figure 4-7. Pertinent data are given in Table 4-1. Shasta, Trinity Folsom, and San Luis are the larger operating reservoirs within the system. Shasta and Folsom Lakes have authorized flood control functions in addition to other objectives. Lewiston, Whiskeytown and Keswick Reservoirs and Lake Natoma (Nimbus) and O'Neill Forebay are essentially regulating reservoirs. San Luis and O'Neill water and power outputs are shared with the State of California according to agreed-on formulas. Either power generating or pumpback modes are possible for San Luis and O'Neill pump-generation plants. San Luis Reservoir stores surplus winter Sacramento-San Joaquin River Delta flows and discharges them through O'Neill Forebay to satisfy summer irrigation demands. Gravity tunnels divert Trinity River water through Judge Francis Carr Powerplant into Whiskeytown Lake and thence through Spring Creek Powerplant into Keswick Reservoir where it combines with Shasta Dam releases. Keswick and Nimbus Powerplants operate at low
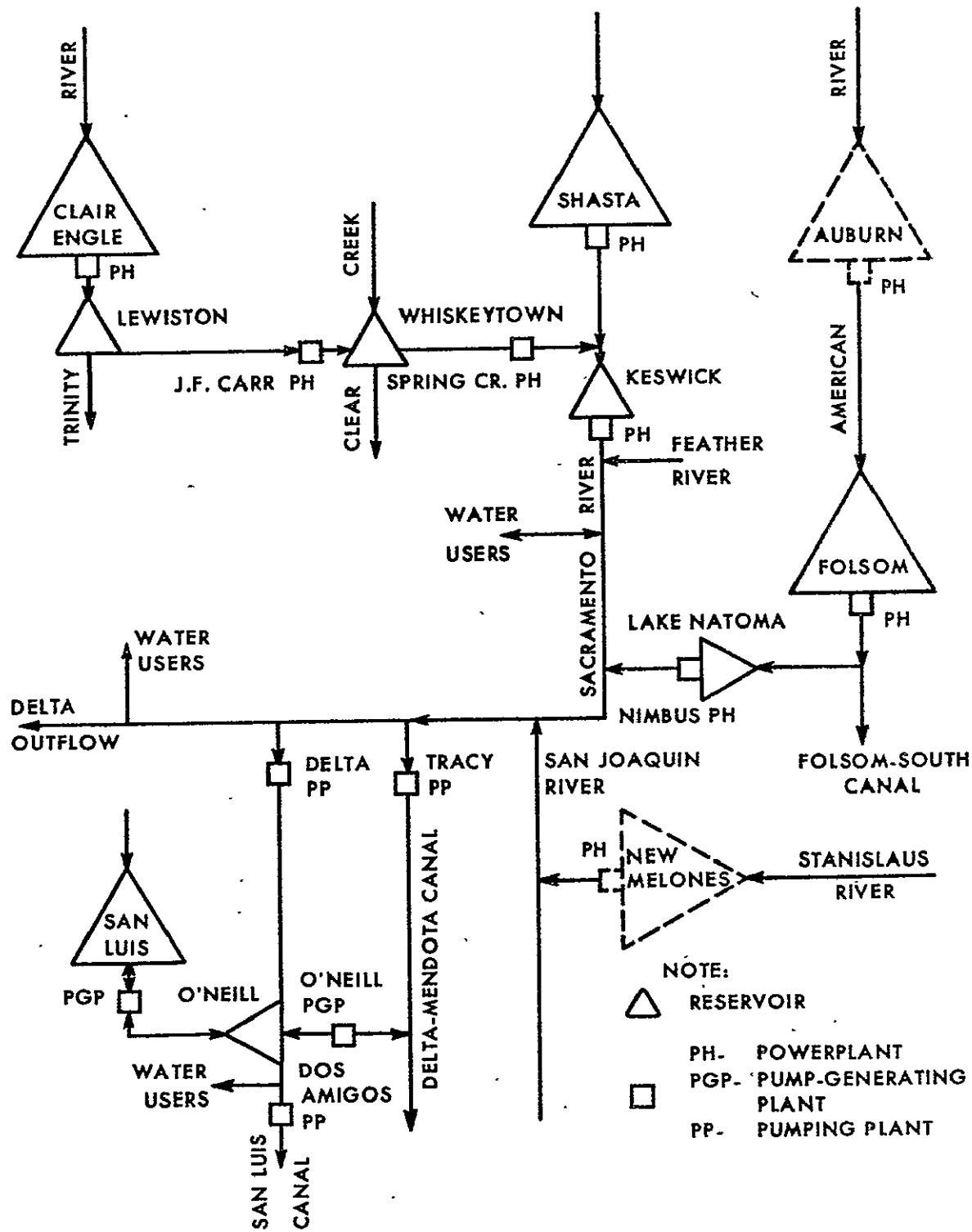
Figure 4-7. CVP System.

Table 4-1. Pertinent CVP Features.

Name of Facility	Capacity Thousands of Acre-Feet (Millions of Cubic Meters)	Functions Served	First Year of Operation
Storage Reservoirs			
Shasta Lake	4,552(5600)	I, FC, P, M&I, WQ, N, R, F	1944
Clair Engle Lake	2,448(3000)	I, P, M&I, WQ, N, R, F	1960
Lewiston Lake	14.7(18.1)	Reg., P, R, F	1963
Whiskeytown Lake	241 (292)	Reg., I, P, M&I, R, F	1963
Keswick Reservoir	23.8(28.8)	Reg., P, R, F	1948
Folsom Lake	1,010.(1240)	I, FC, P, M&I, WQ, R, F	1955
Lake Natoma	8.8(10.8)	Reg. P, R, F	1955
San Luis Reservoir	2,041(2500)	I, P, M&I, R	1967
O'Neill Forebay	56.4(69.5)	I, P, M&I, R	1966

Canals	Cubic Feet Per Second (Meters Per Second)		
Delta-Mendota	4,600(128)	I, M&I, WQ, R, F	1951
Folsom-South	3,500(98)	I, M&I, R	1973
San Luis	13,000(364)	I, M&I	1967

Pumping Plants		(No. of Units)	
Tracy	4,600(128)	6	1951
San Luis	11,000(308)	8	1967
O'Neill	4,200(118)	6	1966
Dos Amigos	13,200(370)	6	1967

Powerplants	Megawatts	(No. of Units)	
Shasta	484	5	1944
Keswick	90	3	1949
Trinity	128	2	1964
Judge Francis Carr	154	2	1963
Spring Creek	190	2	1963
Folsom	198	3	1955
Nimbus	15	2	1955
San Luis	424	8	1967
O'Neill	9	6	1966

I - Irrigation   M&I - Municipal & Industrial   R - Recreation
FC - Flood Control   WQ - Water Quality   F - Fish Protection
P - Power Generation   N - Navigation   Reg. - Regulation

head, whereas, the other powerplants operate at high head. The existing generating units and pumps at each installation and their rated capacities are given in Table 4-1.

Two large dams with appurtenant features are under construction — Auburn and New Melones Dams. Auburn Dam is located on the North Fork of the American River above the existing Folsom Dam and Reservoir. Auburn Dam is designed to create a reservoir of 2.5 million acre-feet and an initial powerplant capacity of 300 megawatts and an utimate capacity of 750 megawatts. New Melones Dam located on the Stanislaus River is designed to create a reservoir of 2.4 million acre-feet and an initial powerplant capacity of 300 megawatts. Each of these facilities is being constructed as an addition to the CVP system. Integration into the overall system operation will occur over a period of time.

The system is subject by contract, interagency agreement, and equipment and facility limitations to a large and varied set of constraints. All of these constraints must be duly considered in performing the sensitivity analysis, and these have been incorporated into the monthly and daily models developed for the CVP.

Table 4-2 shows the monthly inflows into Folsom Lake for the water-years, 1905-1974. The non-uniformity of the inflows from year to year, especially during the snow-melt season, is very evident. Discrepancies between actual and forecast inflows during the snow-melt season can be wide, usually as a result of warm rains or sudden warm weather. The water-year, 1973-1974, although representing a moderately high inflow, is not too unusual, and its hydrology has been used for the analyses.

The unanticipated heavy inflows are indicated graphically by the rising spikes of Figure 4-6, "Operation of Folsom Lake for Flood Control, 1973-1974." Snow-melt events for the test water-year are indicated by Figure 4-5 for Norden station in the American River basin. Hydrologic models are not, as yet, used for daily forecasts in an operational mode.

A daily analysis was conducted for Folsom and Nimbus over a period of 10 years (1964-1974) for anticipations of up to 7 days. The benefits in GWH, in excess of the energy which was actually obtained, were summed for each year and an average annual benefit calculated. Benefits are plotted

Table 4-2. Chronological List of Runoff in Thousands of Acre-Feet.

CHRONOLOGICAL LIST OF RUNOFF IN THOUSANDS OF ACRE-FEET

INFLOW TO FOLSOM LAKE BY WATERYEARS FOR THE PERIOD 1905-1974.   DRAINAGE AREA   1921 SQUARE MILES.

YEAR	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	ANNUAL TOTAL
1904-05	42.0	54.6	82.4	201.0	235.0	378.0	409.0	376.0	179.0	42.7	16.6	8.2	2024.5
1905-06	9.0	11.5	15.6	446.0	379.0	873.0	720.0	928.0	952.0	390.0	62.7	24.9	4761.7
1906-07	18.3	33.5	244.0	255.0	872.0	1520.0	928.0	750.0	660.0	330.0	92.2	48.4	5710.4
1907-08	42.6	48.9	110.0	160.0	113.0	202.0	267.0	282.0	195.0	53.5	12.3	7.3	1453.6
1908-09	23.6	26.2	35.4	1490.0	861.0	397.0	475.0	585.0	455.0	142.0	37.3	17.1	4544.6
1909-10	31.4	273.0	577.0	524.0	291.0	646.0	625.0	489.0	134.0	31.7	13.1	12.0	3647.2
1910-11	21.0	32.0	98.4	855.0	589.0	799.0	898.0	892.0	1050.0	197.0	28.2	18.1	5477.7
1911-12	21.5	25.6	24.6	69.5	46.0	118.0	171.0	421.0	284.0	51.0	12.9	19.6	1264.7
1912-13	14.9	87.5	36.8	96.5	71.6	108.0	359.0	443.0	152.0	37.8	17.4	9.2	1433.7
1913-14	9.5	29.0	132.0	1050.0	389.0	499.0	561.0	719.0	392.0	130.0	27.7	11.4	3949.6
1914-15	20.4	22.3	41.9	95.3	512.0	286.0	506.0	953.0	478.0	109.0	24.0	13.4	3061.3
1915-16	13.3	22.5	80.6	476.0	587.0	806.0	702.0	607.0	399.0	121.0	20.9	13.1	3848.4
1916-17	38.5	38.7	124.0	97.8	407.0	275.0	549.0	633.0	531.0	103.0	22.9	11.8	2831.7
1917-18	11.4	10.8	32.0	17.5	174.0	313.0	440.0	307.0	115.0	19.8	4.3	24.7	1419.5
1918-19	57.8	47.9	47.8	41.6	361.0	314.0	562.0	594.0	95.8	16.5	8.6	8.0	2155.0
1919-20	9.8	9.0	42.3	38.9	37.4	238.0	361.0	439.0	162.0	33.6	10.9	9.3	1391.2
1920-21	34.7	152.0	272.0	473.0	315.0	534.0	432.0	527.0	371.0	76.2	20.0	14.6	3221.5
1921-22	24.5	46.7	136.0	117.0	372.0	338.0	487.0	1020.0	672.0	98.4	22.0	15.7	3349.3
1922-23	30.7	61.3	399.0	268.0	176.0	218.0	566.0	612.0	278.0	97.2	21.6	22.4	2750.2
1923-24	39.7	27.8	28.9	38.1	115.0	54.0	119.0	91.6	12.3	1.6	1.0	1.4	530.4
1924-25	14.4	57.4	99.0	93.5	605.0	319.0	607.0	603.0	258.0	66.4	19.9	16.8	2759.4
1925-26	26.9	32.3	54.9	48.8	259.0	194.0	475.0	197.0	48.3	15.2	10.3	12.3	1374.0
1926-27	21.7	174.0	138.0	223.0	772.0	441.0	726.0	601.0	412.0	76.2	23.4	19.6	3627.9
1927-28	28.2	117.0	103.0	105.0	135.0	990.0	536.0	381.0	79.7	25.5	13.8	13.0	2527.2
1928-29	22.2	33.8	43.3	44.2	102.0	150.0	214.0	341.0	158.0	29.6	10.5	7.7	1156.3
1929-30	6.2	5.1	155.0	137.0	144.0	320.0	343.0	274.0	144.0	25.5	11.1	13.7	1578.6
1930-31	15.9	33.8	20.3	52.9	70.0	132.0	155.0	118.0	38.9	8.4	4.0	5.6	654.8
1931-32	15.4	30.8	171.0	176.0	332.0	295.0	388.0	640.0	402.0	92.2	18.6	13.1	2574.1
1932-33	23.4	30.7	42.6	47.7	54.9	143.0	239.0	352.0	329.0	38.9	15.4	8.5	1325.1
1933-34	25.1	38.9	117.0	165.0	176.0	253.0	184.0	97.8	39.3	11.8	12.1	8.8	1128.8
1934-35	13.5	69.8	71.7	174.4	145.5	208.6	804.0	647.5	345.2	62.0	16.8	13.1	2572.1
1935-36	29.3	42.4	46.5	413.3	776.6	428.3	624.2	572.7	343.9	83.9	28.5	25.0	3414.6
1936-37	30.1	34.2	42.4	55.4	348.6	408.5	507.2	666.6	217.1	53.7	19.4	17.5	2400.7
1937-38	34.1	69.8	442.0	144.2	551.6	809.5	718.4	1003.0	585.9	129.2	35.4	28.9	4552.0
1938-39	42.0	56.5	60.8	66.5	85.9	236.1	309.6	158.8	46.7	10.2	6.5	6.4	1086.0
1939-40	28.2	30.7	42.5	479.5	612.6	847.0	621.6	494.3	192.4	45.1	23.8	24.4	3442.1
1940-41	25.9	56.0	264.3	359.4	484.9	461.2	451.7	702.6	274.1	81.1	28.2	21.1	3212.5
1941-42	29.2	64.0	335.9	595.5	573.4	304.7	625.2	714.0	545.3	147.7	33.3	22.5	3990.7
1942-43	22.2	162.8	297.5	705.9	391.7	945.5	598.8	439.1	258.1	78.2	21.5	14.7	3931.0
1943-44	26.2	36.5	47.9	76.7	160.8	249.8	227.3	461.0	185.5	38.8	13.2	13.3	1537.0
1944-45	27.6	129.6	142.5	111.5	566.3	259.1	408.5	549.7	272.1	66.7	16.6	16.0	2564.2
1945-46	40.8	153.2	540.6	306.3	151.2	342.7	509.0	534.4	193.0	46.3	17.8	22.4	2857.7

Table 4-2.   Chronological List of Runoff in Thousands of Acre-Feet.   (contd)

CHRONOLOGICAL LIST OF RUNOFF IN THOUSANDS OF ACRE-FEET

INFLOW TO FOLSOM LAKE BY WATERYEARS FOR THE PERIOD 1905-1974.   DRAINAGE AREA   1921 SQUARE MILES.

YEAR	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	ANNUAL TOTAL
1946-47	34.3	99.5	102.7	64.9	173.8	294.7	284.4	242.0	86.4	16.7	11.0	8.8	1419.2
1947-48	49.6	52.8	40.9	177.8	86.5	158.1	522.1	624.5	439.2	79.8	18.9	14.3	2262.5
1948-49	28.0	50.1	73.1	66.6	101.3	363.8	507.0	517.5	154.7	22.8	11.3	9.8	1906.0
1949-50	15.2	35.7	38.6	316.6	348.6	346.5	586.3	588.4	318.7	73.4	17.2	20.2	2704.9
1950-51	56.7	978.7	1067.0	594.4	434.2	432.8	424.9	456.9	149.3	38.3	18.1	16.2	4667.5
1951-52	42.2	113.1	334.3	555.9	559.4	501.8	817.9	1119.0	660.4	238.6	56.5	31.3	5030.2
1952-53	78.2	33.0	120.1	469.7	157.1	231.9	467.5	489.2	499.9	158.4	27.5	24.0	2706.5
1953-54	34.4	63.1	84.6	140.5	270.2	451.4	546.6	358.4	103.6	27.4	15.0	20.7	2067.9
1954-55	26.6	46.4	137.2	164.1	106.8	164.1	245.6	486.4	218.5	41.7	26.5	26.8	1685.7
1955-56	36.0	-49.1	1261.2	977.3	340.5	334.6	419.5	770.8	420.2	114.5	29.2	28.4	4781.3
1956-57	53.4	61.8	70.6	77.5	300.4	455.2	317.0	566.7	293.2	57.4	22.0	21.4	2296.6
1957-58	45.4	60.8	113.6	172.5	597.9	579.3	861.7	1042.3	532.3	129.8	40.6	29.2	4205.4
1958-59	34.3	46.2	37.2	160.4	214.1	205.6	290.0	202.2	80.0	22.4	11.4	21.6	1315.4
1959-60	26.6	23.6	28.5	73.1	361.3	441.7	356.3	276.3	118.6	26.8	14.8	13.1	1760.7
1960-61	23.4	54.3	70.8	45.3	128.5	157.6	238.7	267.4	120.1	34.5	24.8	17.1	1180.5
1961-62	19.3	33.1	73.9	69.6	423.3	251.3	541.6	398.4	237.8	58.2	36.7	27.8	2171.0
1962-63	374.8	70.8	182.6	244.1	682.8	216.9	613.2	660.4	278.8	66.4	23.5	24.3	3386.6
1963-64	106.6	244.3	146.0	218.0	131.0	124.9	255.7	325.6	180.1	75.8	65.0	43.3	1914.3
1964-65	29.3	99.2	1328.4	787.5	324.0	241.3	558.3	480.7	271.5	138.2	89.7	73.1	4421.2
1965-66	80.7	107.1	152.3	169.8	133.7	198.8	267.1	174.6	79.4	57.9	54.1	46.0	1516.5
1966-67	52.7	92.9	293.8	435.3	293.5	517.7	477.4	712.4	582.4	282.7	146.4	99.8	3987.0
1967-68	93.2	125.0	152.1	175.8	349.6	231.4	198.0	172.7	111.8	72.9	86.1	76.0	1844.6
1968-69	94.7	137.3	185.1	993.2	591.2	457.3	608.1	653.9	386.0	170.8	146.9	124.3	4548.8
1969-70	108.5	141.3	326.3	1128.2	391.8	335.5	204.7	233.6	191.5	103.9	124.0	90.7	3380.0
1970-71	102.1	209.8	427.7	333.0	240.7	334.2	300.4	354.3	313.6	169.8	143.7	111.1	3040.4
1971-72	105.0	96.3	191.2	201.6	276.0	302.8	241.5	227.5	140.4	99.4	136.4	99.8	2067.9
1972-73	103.5	139.9	252.6	595.4	453.0	407.9	305.9	374.9	172.8	92.5	93.7	101.0	3093.1
1973-74	90.9	350.2	448.0	682.8	284.6	699.3	597.0	494.8	329.1	177.3	132.2	126.6	4407.8
TOTALS	2906.7	6135.0	13571.8	21482.8	22905.8	27092.4	32446.9	35488.9	20347.9	5947.7	2499.9	2001.7	192862.5
MEAN	41.5	87.6	193.9	306.9	377.2	387.0	463.5	507.0	291.0	85.2	35.7	28.6	2755.2
PERCENT	1.5	3.2	7.0	11.1	11.9	14.0	16.8	18.4	10.6	3.1	1.3	1.0	99.9

| 74-75 | 112.6 | 120.0 | 115.8 |

against anticipation in Figure 4-8. In addition, the daily analysis for the month of December 1973 was extended to 25 days anticipation of a high inflow event — an anticipation which may be possible in the future with better snow-pack and snowmelt information. ·For reference purposes, similar analyses were made for Trinity for January 1974 and for Shasta for February 15 - March 15, 1974. These periods included significant high inflows. These results are also shown in Figure 4-8.

In general there is a leveling off of the benefits curve with time — a result of either complete recovery of the spill produced by the inflow event, or of encountering a period in which the power release was already near or at the maximum or both. The most meaningful results are those given by the Folsom average annual benefits curve, since these benefits were obtained for a representative sampling of hydrologic situations and for both wet and dry seasons of the year. This curve shows, for example, that for five days antici-pation of a high inflow event (the two components of the anticipation time are the forecast of the rainfall or snowmelt and the lag time from precipitation on the watershed to flow into the reservoir) the benefits are approximately 2.5% of the average annual generated energy.

The Folsom annual curve can be reasonably extrapolated to the other major reservoirs of the Central Valley Project on the basis of a comparison of the monthly benefits curves of Figure 4-8. The extrapolated annual benefits would be:

	GWH	
	Shasta	Trinity
3 days	30	45
5 days	48	80
7 days	72	120
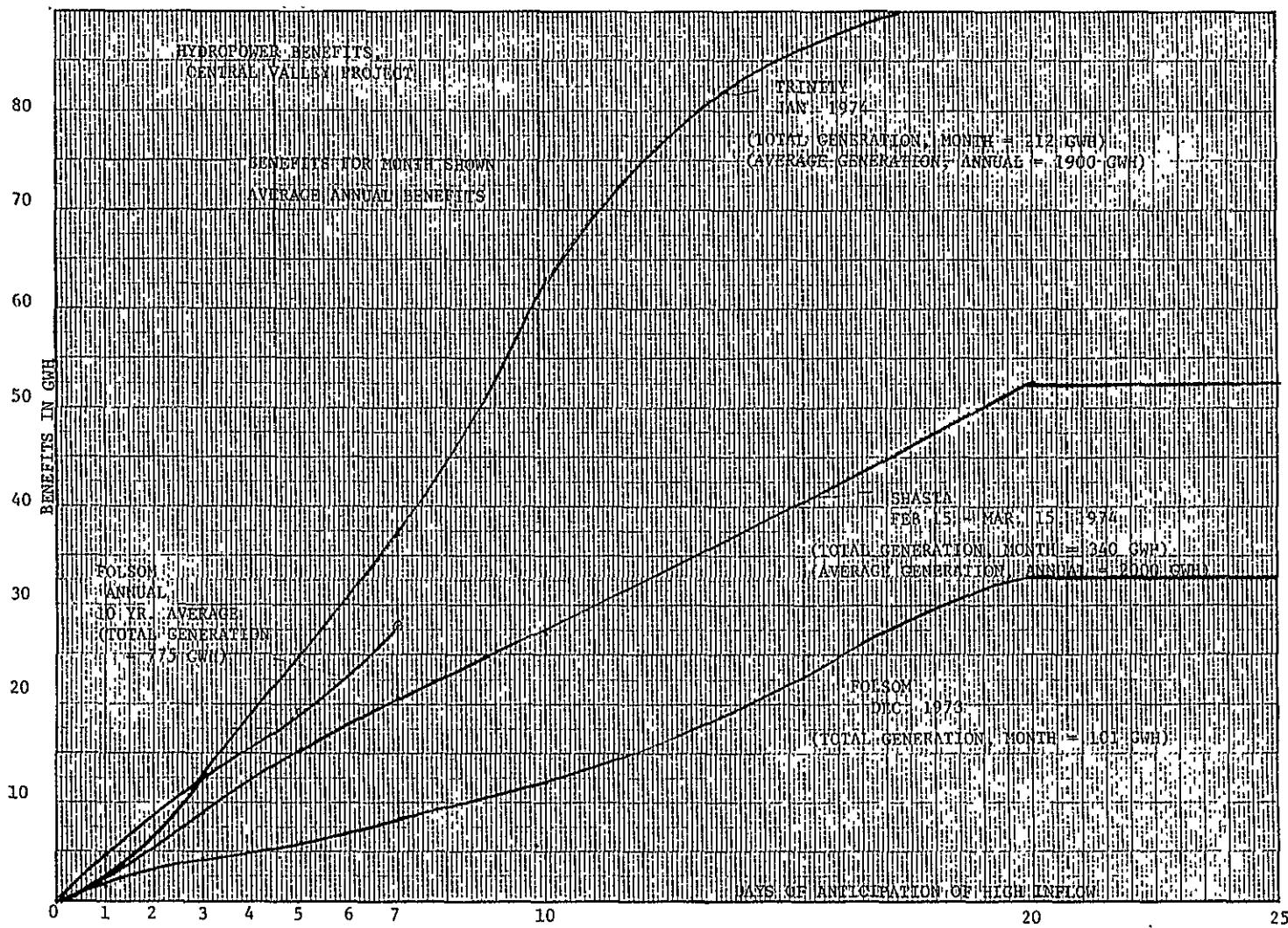
Figure 4-8.   Hydropower Benefits — Central Valley Project.

A rough extrapolation to all of Northern California can be made on the basis of installed capacities. This would give:

3 days	200 - 300 GWH
5 days	350 - 550 GWH
7 days	600 - 800 GWH

It has been indicated that the magnitude of the high inflow need not always be forecast with 100% accuracy so long as the fact that a high inflow event is about to occur is forecast. However, the requirement for high accuracy does depend on the number of days of anticipation and on the size of the high inflow relative to the available power storage. The accuracy requirement for a two-day anticipation of a large storm can be substantially less than that for a seven-day anticipation of a small storm. This type of dependence can be calculated from the data of Table 4-3 which shows the actual spills that occurred for the high inflows into Folsom during the years, 1964-1974, and the decrease in spill possible with anticipation assuming 100% accuracy in forecasting the magnitudes of the event. (The average annual Folsom curve of Figure 4-8 was obtained from similar data.) For example, considering the data of the event of 3/67, a 50% underestimate of spill, or a spill of 50 KAF, would not change the benefits for one or three-days anticipation but would decrease the benefits for five and seven days to the equivalent of a 50 KAF decrease in spill. Overestimates would not change the benefits for that event with anticipation limited to seven days. Overestimation would decrease benefits lightly in the case of the event of 1/67 (a) for three days of anticipation upward because of a somewhat lower average operating head than would correspond to perfect information. This would also be true for a number of other events listed in the table. However, this small effect has been ignored and only the more severe consequences of underestimation have been determined and are displayed by Figure 4-9. Nevertheless, if a sufficiently high probability forecast of a high inflow event can be made, a rational hydropower operator might choose to bias towards overestimation for a limited period of time (several days) by releasing water at the maximum power rate or at rate corresponding to the product of the maximum rate and the forecast probability.

Table 4-3. Folsom Reservoir — Decrease of Spill with Anticipation of High Inflow.

ANTICIPATION OF HIGH INFLOW IN DAYS	DECREASE IN SPILL (KAF) PER HIGH INFLOW EVENT OCCURRENCE																					
	12/64	12/66	1/67 (a)	1/67 (b)	3/67	2/68	1/69 (a)	1/69 (b)	2/69	12/69	1/70	11/70	3/71	12/72	1/73	2/73 (a)	2/73 (b)	11/73	12/73	1/74	3/74 (a)	3/74 (b)
1	8.3	2.6	12.6	3.6	6.5	6.5	6.5	6.5	3.2	12.5	2.0	5.6	12.6	6.5	6.5	2.6	5.4	6.5	12.2	0.7	12.4	6.5
3	31.1	17.6	18.0	22.9	29.2	22.0	20.0	14.7	5.0	35.2	15.0	23.9	18.0	7.7	21.4	9.8	17.7	25.0	36.2	7.5	28.3	19.5
5	56.1	30.0	18.0	22.9	54.2	45.9	20.0	15.9	5.0	60.1	28.1	46.6	18.0	7.7	42.8	25.2	29.3	46.2	61.0	15.3	43.9	32.5
7	81.1	30.0	18.0	22.9	79.2	60.0	20.0	15.9	5.0	72.0	47.5	59.0	18.0	7.7	62.9	47.8	39.4	48.0	62.0	19.8	59.9	43.1
ACTUAL SPILL (KAF)	1022.	30.	18.	93.	99.	60.	20.	472.	101.	72.	683.	59.	18.	7.7	202.	48.	50.	48.	62.	175.	76.	100.

NOTES: (1)(a), (b) Designate 2 individual events in same month

(2)   1 KAF decrease of spill ~ 0.27 GWH of energy

(3)   Mean annual energy generated ~ 775 GWH
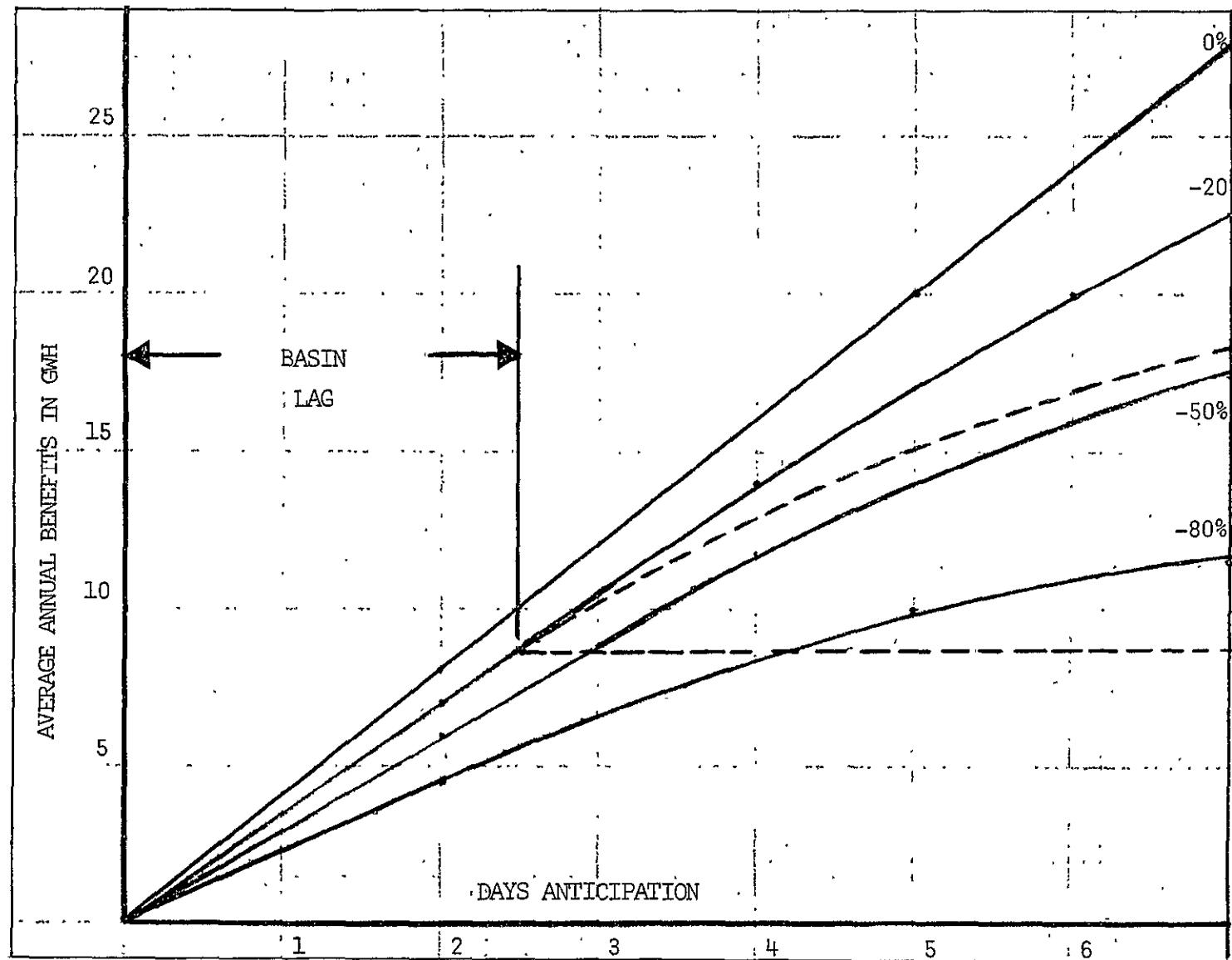
Figure 4-9. Annual Benefits vs. High Inflow Anticipation and Underestimate
of Magnitude, Folsom Reservoir. (Average Annual Generation = 775 GWH).

Figure 4-9 shows that, if releases are made on the basis of forecasts of streamflow magnitudes, benefits will fall off, on the average, with the percentage underestimate. The fall-off increases with increase of estimation error and with anticipation time, although the effects are reasonably linear for up to three days of anticipation and for up to 50% underestimation. However, it should be noted that if the percentages shown on the figure represent standard errors rather than underestimates, the loss in benefits with increase of error can be expected to be less, since over and underestimates may be equally likely depending on the watershed model and the instrumentation used. On the other hand, operators have traditionally devalued inflow forecasts, this being the conservative action from their point of view.

The basin lag for the American River is approximately 2-1/2 days. If it is assumed that all model, measurement, and sampling errors (no prediction involved) integrate to a -20% error, an expected decrease in prediction error with approach of the high inflow event and the subsequent forecast updating procedure would be typified by the dashed curve of Figure 4-9. The horizontal dashed line indicates the benefits if no prediction were attempted.

An anticipation of a high inflow event can also pay off in hydropower benefits by allowing a reduction in the reserved flood control space and thus an increase of the power pool. Thus, it can be computed that, for a flood condition predictability of 1, 1.5, and 2 days for Folsom and operating within existing release rate regulations, the following reduction in reserved flood control space can be made.

Case 1	1 day	72 KAF
Case 2	1.5 days	167 KAF
Case 3	2 days	277 KAF

With these reductions the additional benefits shown in Table 4-4 and plotted in Figure 4-10 can be achieved.

It should be noted that approval of reduced flood control space would be highly contingent on extended field tests of flood condition predictability with positive results. Even then, it might be decided to thereby gain

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Table 4-4. Benefits Obtainable from Flood Control Space Reduction
Folsom Reservoir

Inflow Anticipation Days	Average Annual Reduction Spills, KAF and (Additional Benefits, GWH)		
	Case 1	Case 2	Case 3
1	50.1 (12.5)	76.5 (21.2)	93.1 (29.1)
3	41.3 (10.3)	65.6 (18.2)	81.3 (25.4)
5	32.0 (8.0)	55.2 (15.3)	70.2 (21.9)
7	27.5 (6.9)	49.1 (13.6)	63.4 (19.8)

additional flood control benefits rather than hydropower benefits. The direction taken in any such situation would be somewhat subjective and would undoubtedly depend on circumstances and problems encountered in prior years.

Columbia River Mainstream

Amost half of the entire hydropower capacity of the country is in the Pacific Northwest (about 20,000 MW). Fifteen hydropower plants with diverse ownership (Corps of Engineers, Bureau of Reclamation, public and private utilities), on the main stem of the Columbia River and on the lower Snake River, comprise more than half of the Pacific Northwest capacity and about 70% of the generation capability under a "Pacific Northwest Coordination Agreement." These plants and their individual capacities are shown on Figure 4-11. Grand Coulee is the only facility with seasonal storage. The others are pondage reservoirs although John Day has appreciable storage (300 KAF). Each plant also has local tributary inflow. Short term optimization, for one week in eight hour segments, are conducted for these plants; the purpose of the optimization is to minimize local spilling and expenditure of system energy, while conforming to load demand and other system constraints and institutional agreements. Grand Coulee releases conform to the results of an overall long-term optimization, conducted once a year and
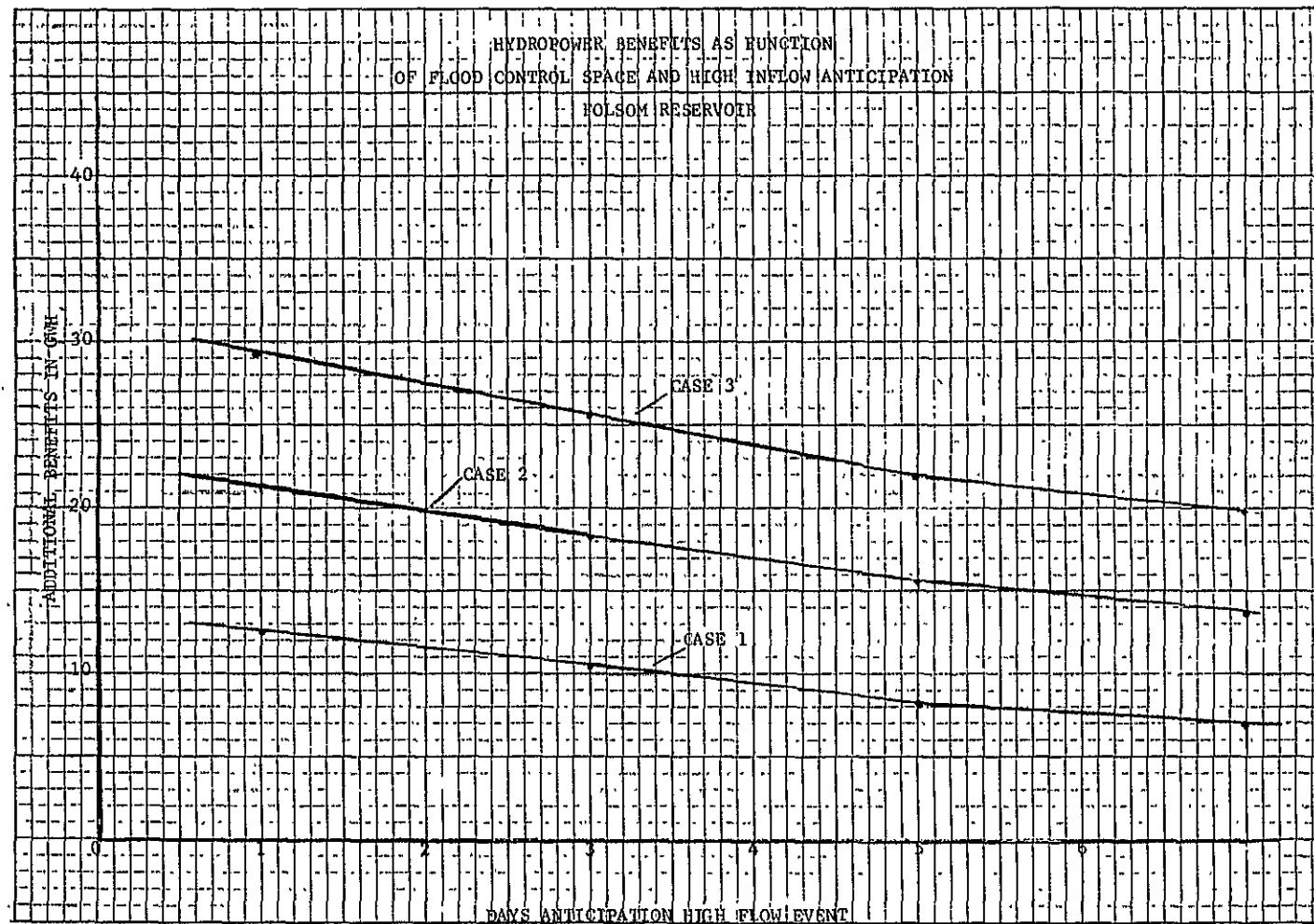
Figure 4-10. Hydropower Benefits as Function of Flood Control Space
and High Inflow Anticipation Folsom Reservoir.
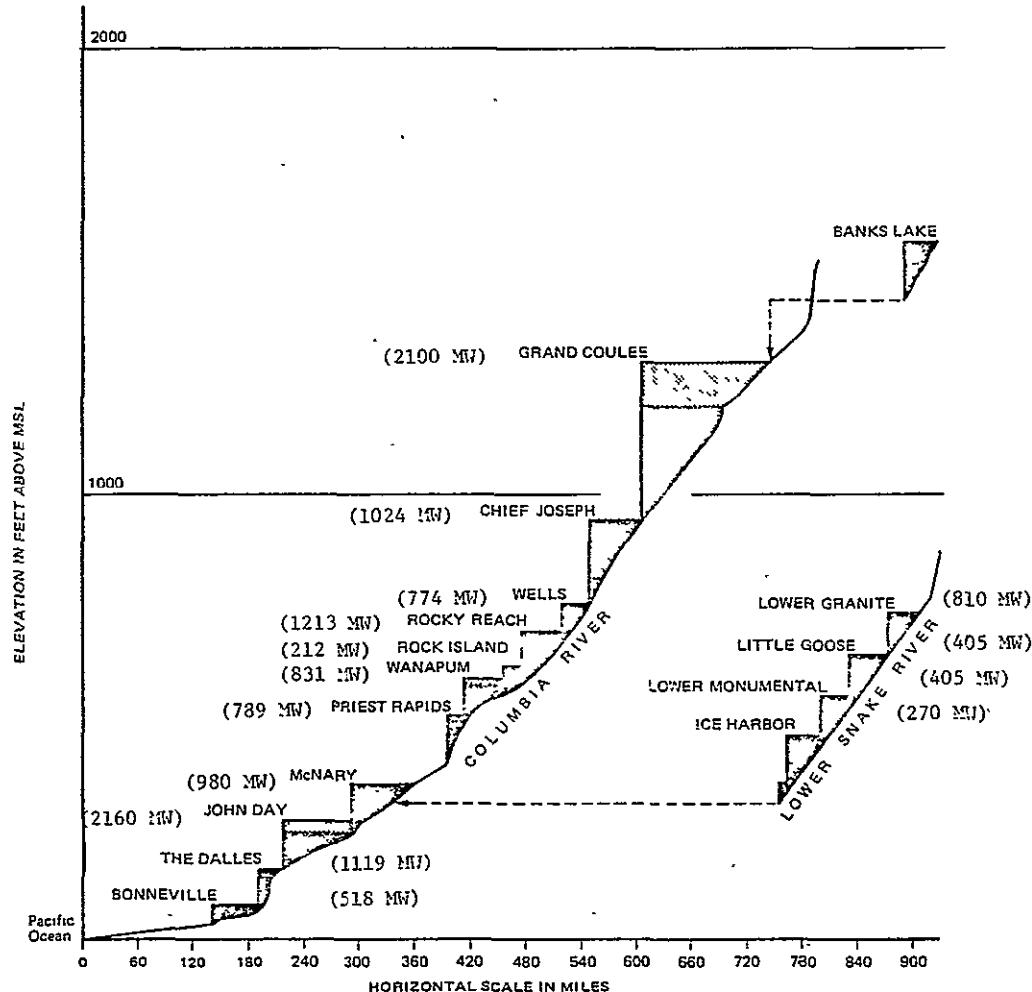
Figure 4-11. Profile — Columbia River Main Stem and Lower Snake River.

based on the basin critical hydrology rather than on long-term forecasts, and modified by institutional compromises.

A historical data tape containing seven years of very detailed daily information of plant generation, inflow, outflow, power release and spill for each plant, amongst others, was obtained from the Corps of Engineers, Portland, Oregon. The data was analyzed and several distinct patterns could be noted. Spring (and summer) runoff from snowmelt is dominant; rainfall runoff also contributes to the spring high flows, and during autumn and winter causes relatively minor fluctuations in the river flow, particularly between Grand Coulee and the confluence of the Columbia and Snake Rivers. Part of this flow is regulated and consists of mandatory releases from large upstream storage reservoirs. A second characteristic is the occurrence of continued heavy spilling at all plants during the high flow season. Such spilling often masked the spill that might have occurred as the result of a rainstorm event, as in the case of the Central Valley Project. This heavy spilling arises from the disparities between maximum hydropower releases and the very heavy spring flows. A third characteristic is the very frequent power release at less than maximum while simultaneously spilling water. Although this will happen when there is a temporary outage of units at a plant, it appears that in most cases it is a result of insufficient load demand by the present power markets, and energy is unnecessarily lost, especially during off-peak hours. A further influence is a local (Pacific Northwest) shifting of base load to newly online thermal plants and a shifting of hydropower towards onpeak peaking capacity usage.

Nevertheless, it was estimated from consideration of the inflows, power releases, and spills at each plant that the following average annual benefits could be obtained from anticipation of large snowpack and subsequent snowmelt and high inflows, provided that maximum power releases could be made and markets were available for the generated energy.

    a.   Chief Joseph to Priest Rapids

        1 day anticipation high inflow — 49.0 GWH
        2 days anticipation high inflow — 92.9 GWH

b. McNary to Bonneville

1 day anticipation high inflow — 23.4 GWH

2 days anticipation high inflow— 59.6 GWH

In general, benefits of this type (involving pre-release from pondage storage) beyond two days were not possible because of storage limitations.

c. At Grand Coulee

1 month accurate forecast of snowmelt runoff — 250 GWH

2 months forecast   — 520 GWH

The latter constitutes about 3.5% of annual generation.

d. At all pondage plants downstream of Grand Coulee.

As a result of the more beneficial regulation of Grand Coulee releases due to better forecast information, and thus of better regulated river flow, very substantial benefits, larger than at Grand Coulee, are probable. However, an accurate estimate on the basis of the historical data alone is not possible. To do so would require a consideration of all system constraints and an optimization or scheduling routine.

Thus, better anticipation and more accurate forecasting of the inflows into Grand Coulee can result in large benefits from decreased spill at Grand Coulee and all downstream facilities, provided that the energy so gained, especially at offpeak hours, can be marketed. Considering the existing Pacific tieline, the energy requirements of the California coastal cities, and the delay and cost in constructing new thermal plants, this may not be unreasonable.

Upper Missouri Basin

The Upper Missouri Basin contains six large hydropower facilities situated on the main stem of the Missouri River. These facilities, operated by the Corps of Engineers, have flood control and navigation functions as well as hydropower capabilities, and three of the reservoirs rank with the largest in the country with respect to both maximum storage and size of the power pool. The facilities are shown on Figure 4-12, and their characteristics are given in Table 4-5. The table indicates that Fort Peck, Garrison,

1975

FT. PECK

GARRISON

OAHE

BIG BEND

FT. RANDALL

GAVINS POINT

► TRIBUTARY RESERVOIRS
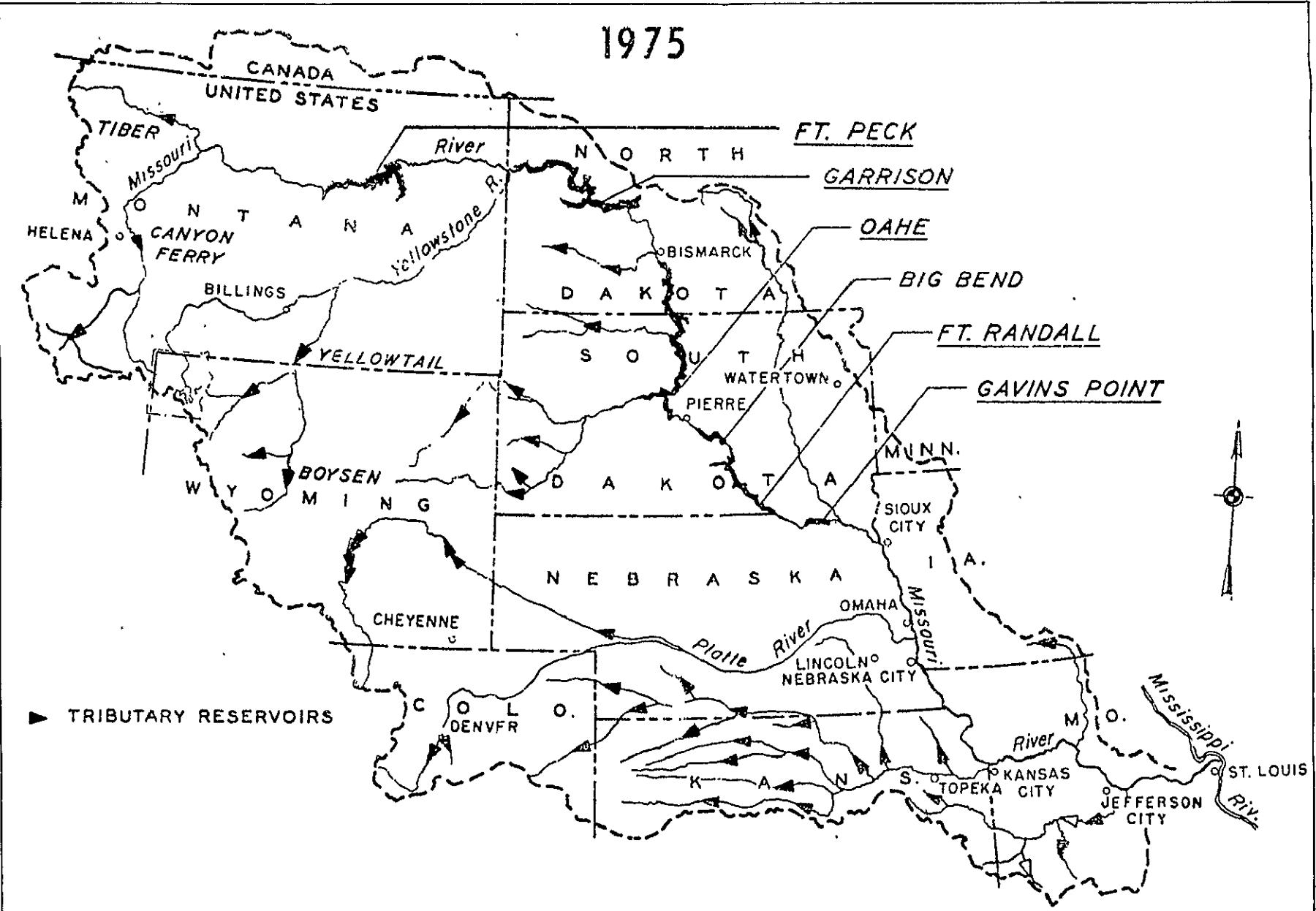
Figure 4-12.   Missouri River Basin.

Table 4-5. Missouri Main Stem Hydropower Facilities.

DAM	RESERVOIR STORAGE ALLOCATION (KAF)					INSTALLED CAPACITY MW	AVERAGE ANNUAL GENERATION GWH	MAX POWER RELEASE CFS
	INACTIVE	CARRYOVER MULTIPLE USE	FLOOD CONTROL & MULTIPLE USE	EXCLUSIVE FLOOD CONTROL	TOTAL STORAGE			
FORT PECK	4300	10900	2700	1000	18900	165	960	15000
GARRISON	5000	13400	4300	1500	24200	400	1886	36000
OAHE	5500	13700	3200	1100	23500	595	2027	55000
BIG BEND	1465	270	0	175	1910	468	871	>100000
FT. RANDALL	1200	2200	1300	1000	5700	320	1503	45000
GAVINS POINT	165	195	100	60	520	100	608	35000

and Oahe have substantial carryover storage from year to year and thus, in spite of the very large power pool, spilling is not too improbable. Nevertheless, little spill occurred until the very large inflow events of 1975. Fort Randall and Gavins Point did spill in the years 1969-1972 in addition to 1975. These reservoirs are downstream of the others and spills occurred to avoid infringement of the exclusive flood control space of the upstream reservoirs. Figure 4-13 shows the ten-year history of releases and storage for the main stream reservoirs of interest.

It can be estimated from the releases shown in the figure and from the data of Table 4-5 that an average annual 5 GWH could be saved at Gavins Point and 4.4 GWH at Fort Randall if releases could be increased sufficiently prior to the spring snowmelt season, that is, during the winter. However, not only are these benefits quite small, but there is substantial ice formation and breakup downriver below Sioux City during those months, and the maximum allowable winter releases are designed to avoid potential flooding as a consequence of ice jams. Since reliable forecasts of such jams can only be made for a time considerably less than the transit time of a release to the vulnerable downriver area, winter releases from Gavins Point are restricted to a maximum of 20,000 cfs. Such a restriction cancels out almost all hydropower benefits that might have been obtained from large pre-snowmelt releases based on more accurate knowledge of the snowpack or on early and rapid snowmelt prediction.

Since these reservoirs make up the bulk of the hydropower capability of the Upper Missouri Basin, it is concluded that no appreciable hydropower benefits for that basin can be obtained from a better runoff prediction capability. Parenthetically, there may be a possibility that earlier prediction of ice jamming could be achievable through remote sensing with resulting hydropower and flood damage benefits in this and other northern regions.

4.4.2 Hydropower Benefits vs. Parameter Errors

The Folsom results can be combined with the parallel sensitivity analysis of the watershed runoff model representing the American River drainage to yield hydropower benefits as a function of the watershed parameters for the Folsom facility. The measurable parameters can then be ranked
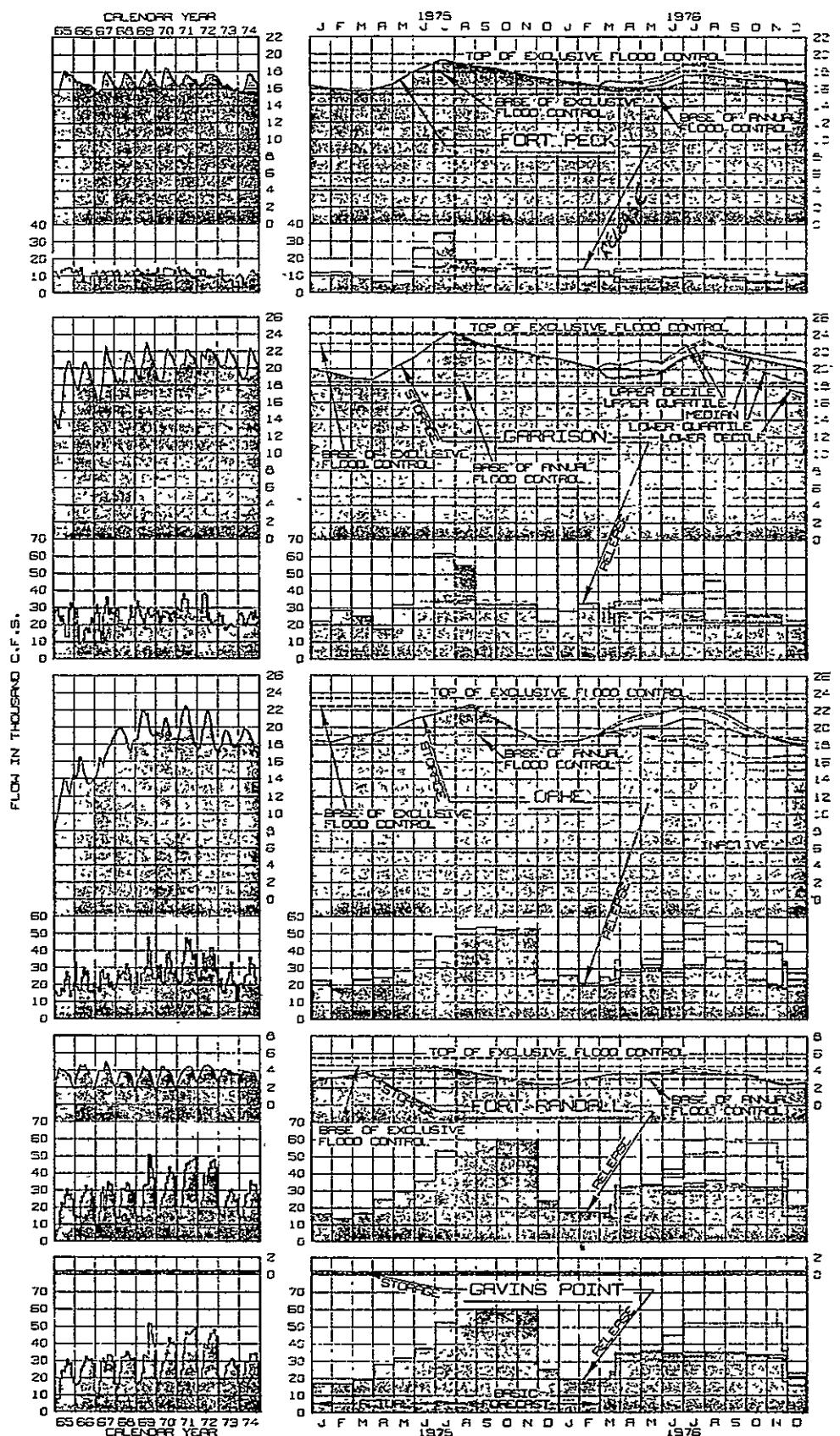
Figure 4-13. Missouri River Main Stem Reservoirs —
1975-1976 Operating Plan.
Water Scheduling

4-45

to provide an indication as to the types of sensors which will yield the higher payoffs. Conversely, the benefits resulting from the use of specific sensors could be obtained, at least with reference to the Folsom output.

The more important measurable parameters and their sensitivities have been selected from the watershed analyses and are shown in Table 4-6. The values given in the table are the fractional changes in the runoff $\Delta V/V$, where the runoff is totalled only for those runoff rates in excess of the maximum power release through the turbines, for various percentage changes in the parameter. This is clearly the important sensitivity criterion for our purpose since all lower rates can be released as necessary to avoid spill. The sensitivities for both positive and negative changes in the parameters are given, and, in general, the sensitivity relationship is non-linear. In accordance with the previous discussion only those parameter changes which result in underestimates of runoff were considered.

"Precipitation" includes both rainstorm and snowmelt and is clearly the most significant variable. The variables pertaining to the moisture content of the top layers of soil, the initial content, $(I.C.)_1$, and the maximum content, P_1, rank next in significance. Evapotranspiration has a small effect, principally because in March it is basically low.

However, if $(I.C.)_1$ can be directly measured only infrequently, and is instead derived from the day by day operation of the model, errors in evapotranspiration can substantially affect the estimate of $(I.C.)_1$. P_{13}, the impervious fraction of the basin, also has a small effect.

Hydropower and watershed sensitivities are combined in Figure 4-14.

It is evident that there is a dropoff in annual benefits with increased error in estimating the parameters (in the direction of underestimating run-off), particularly for precipitation and the upper zone tension water parameters. The greater the anticipation of the high runoff event, the sharper the dropoff. However, it is also clear that even large estimation errors will not completely annul benefits. It should be noted that these errors are considered to be averaged over the entire basin, and since ground instrumentation can be installed at relatively few stations in the basin, remote sensing need not be more accurate per se, but can serve to reduce the often large sampling errors.

Table 4-6. Runoff Sensitivities for Selected Watershed Parameters —
American River, March 1957.

($\Delta V/V$ are Listed in Table Where V = Total Runoff Above Rate
Corresponding to Maximum Power Release.)

Quantity	% Change In Quantity									
	-50	-40	-30	-20	-10	10	20	30	40	50
Precipitation	- .91	- .81	- .7	- .5	- .25	.41	.84	1.42	2.06	2.9
Evapotranspiration	.11	.08	.06	.03	+.01	- .01	- .03	- .04	-.05	- .04
$(I.C.)_1$	- .62	- .52	-.40	- .26	- .09	VALUE ALREADY AT MAX.				
P_1	.84	.6	.4	.25	.13	- .09	- .26	- .4	- .52	- .62
P_{13}	- .09	- .07	- .05	- .04	- .02	.01	.01	+.02	.02	.03

NOTES

(1) PRECIPITATION INCLUDES SNOWMELT

(2) $(I.C.)_1$ IS INITIAL UPPER ZONE TENSION WATER CONTENT

(3) P_1 IS MAXIMUM UPPER ZONE TENSION WATER CONTENT

(4) P_{13} IS IMPERVIOUS FRACTION OF BASIN
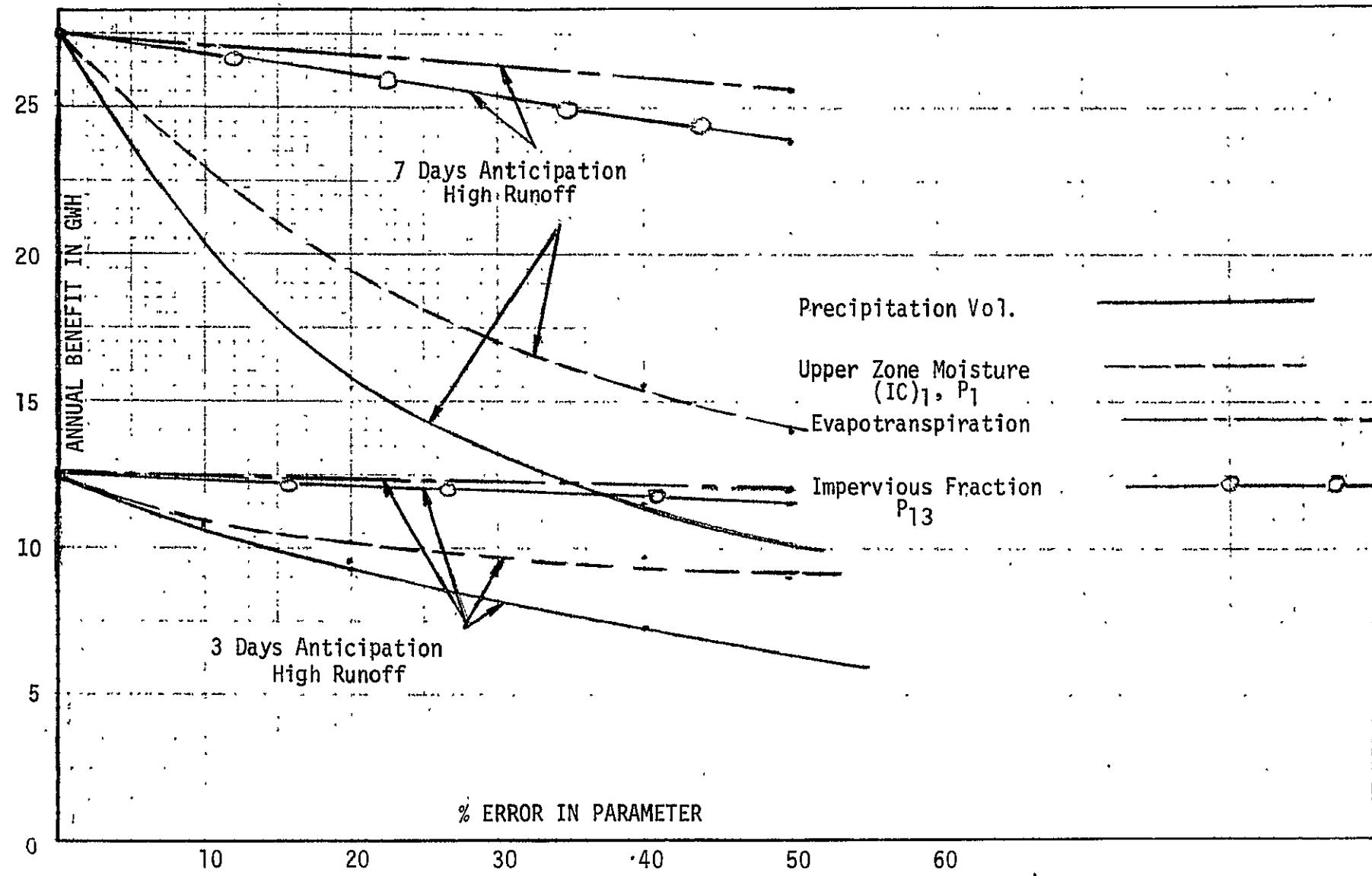
Figure 4-14. Benefits as Function of Watershed Parameter — Folsom.

Since the American River snowmelt model offered few possibilities for remote sensing, specific snowmelt parameters were investigated through the use of snowmelt routines in the SSARR model.

The more important measurable snowmelt model parameters and their sensitivities are shown in Table 4-7. The values in the table are the percentage change in "Moisture Input" to the basin resulting from the snowmelt and can be treated in a similar fashion to the percentage change in precipitation. The most significant parameters in the case of this single example of this particular model appear to be the snow covered fraction of the basin and the insolation.

The parameter sensitivities shown in the table have been combined with the precipitation benefits of Figure 4-14 to give the benefit functions of Figure 4-15. It is noteworthy that substantial benefits can be realized, even for large estimation errors, provided that a high runoff event has been sufficiently anticipated. It must be emphasized that the benefit functions of Figure 4-15 represent only a single isolated case; however, it is clear that substantial estimate errors in a number of the parameters will not severely diminish benefits provided that there is high inflow anticipation, and provided a parameter such as fraction of area snow covered (for the model) is adequately estimated, for example, within 10% of the true value. Benefits as functions of other important snowpack parameters such as mass, density, depth, liquid water content, and structure could not be determined since the model did not embody these parameters.

4.5   Summary and Conclusions

For a majority of hydropower facilities, the dominant energy loss mechanism is the spilling or forced release of water beyond turbine capacity (or market capability to absorb the generated power), available storage in the reservoir space reserved for the power pool being inadequate. Much of this spill results from insufficient information or inaccurate forecasts of expected reservoir inflows. In the face of such uncertainty the hydropower operator must maintain conservative levels of the power pool to reasonably assure his contractual obligations, and spill as a·consequence of a high inflow event becomes quite possible. More complete and timely inflow

Table 4-7. Snowmelt Parameter Sensitivities SSARR Snowmelt Model, April 1968.
(Tabulated Values are Percentage Changes in Snowmelt Moisture Inputs to Basin.)

Quantity (Reference Value)	% Change in Quantity									
	-50	-40	-30	-20	-10	10	20	30	40	50
Fraction Area** Snow Covered (0.71)	-35	-26	-18	-11	-5	4	8	10	10	10
Air Temperature* (35.5°F)	Depresses Temp. Below Freezing				-2.2	1.2	1.8	2.1	2.2	2.4
Insolation (600 Langleys)	-10.4	-7	-4.4	-2.5	-1	0.8	1.3	1.6	1.8	1.9
Albedo (0.4)	1.7	1.5	1.3	0.9	0.5	-0.7	-1.5	-2.5	-3.7	-7.2
Effective Forest Cover Ratio (0.4)	1.2	1	0.8	0.6	0.3	-0.3	-0.7	-1.2	-1.7	-2.2
Wind Velocity (10 mph)	-6.1	-4.9	-3.7	-2.4	-1.2	1.2	2.4	3.7	4.9	6.1

* Positive values used in benefits calculations to simulate negative perturbations from higher temperature

** Watershed area - 5580 sq. mi.
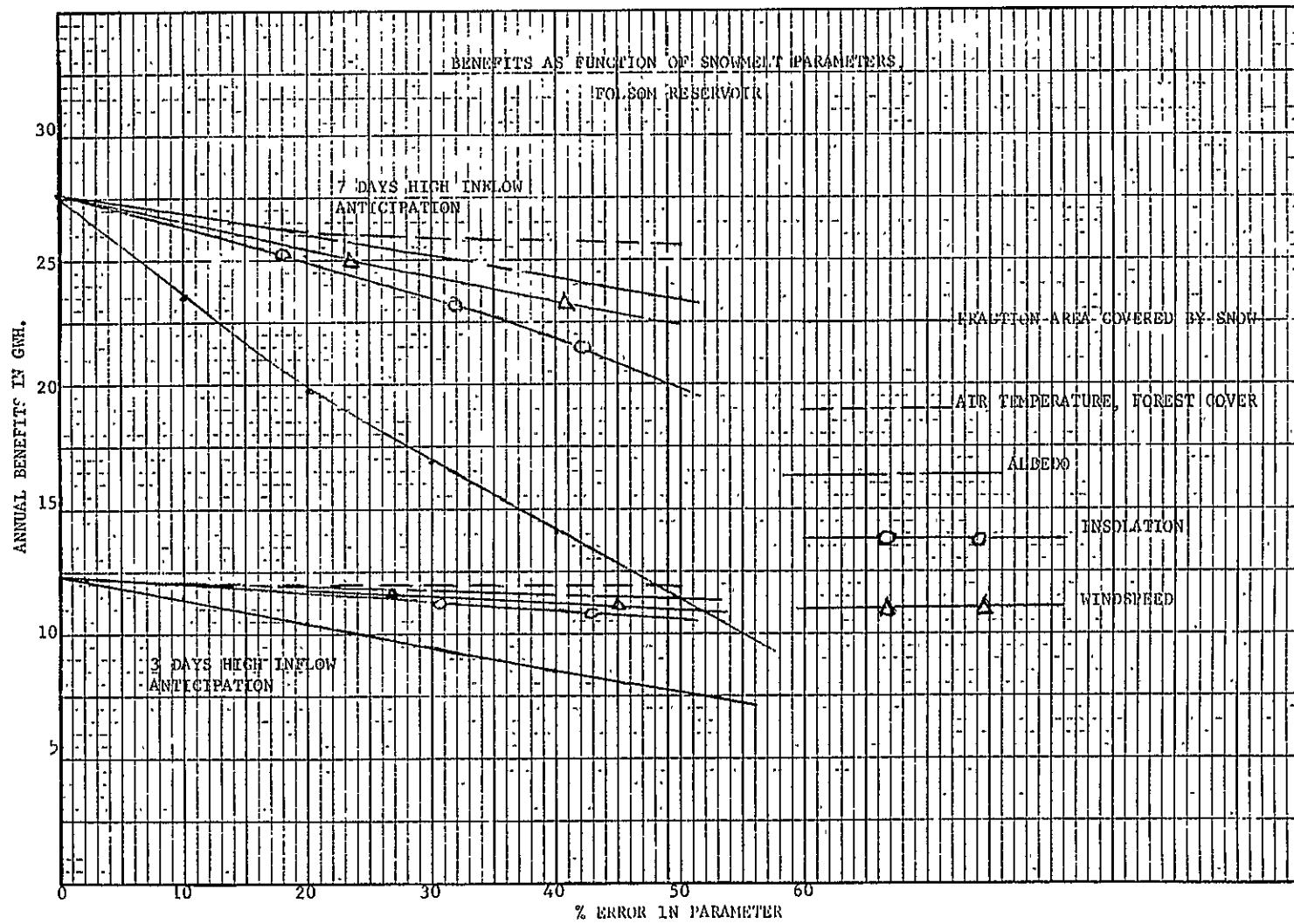
Figure 4-15. Benefits as Function of Snowmelt Parameters —Folsom Reservoir.

information than currently prevails will enable an increase in hydropower productivity while maintaining the same degree of conservatism in operation of the facility. However, such increase is essentially limited at present by the difficulty in making accurate climatic forecasts over extended periods of time and by the maximum control action (maximum power release) possible each day of high inflow anticipation. Consequently, at the present time, the hydropower benefits are no greater than several percent of average annual generation at a facility. Additional benefits can be gained if forecasts are sufficiently reliable to enable relaxation of flood control space requirements; these gains may be several more percent of the average annual generation.

In view of the limited look ahead possibilities, it is essential that emphasis be placed on instrumentation and procedures which can provide timely indications of high inflow events. Snowpacks offer interesting possibilities in this regard, and sensors which can provide adequate information as to runoff from snowmelt as a function of time will have considerable payoff. It is noteworthy that most watershed models do not furnish the information and are deficient in snowpack parameters which would enable runoff determinations on a daily basis. The reason is that effective sensors for measuring these parameters have been lacking, and models have resorted to statistical correlations and calibrations for this purpose. However, high inflow events, by their nature, often do not conform to statistical patterns, and such methods are not satisfactory for our purpose.

In some few instances seasonal volume inflow forecasts, based on the apparent water equivalence of a snowpack and updated relatively frequently, may show significant benefits if these forecasts are sufficiently accurate. Such benefits can occur for systems with very large storage reservoirs and corresponding power pools, where the power pools may be drawn down at a maximum rate over a considerable period before being replenished by large snowmelt runoffs, and thus avoiding spill. Most large reservoirs, however, rarely spill and thus few benefits are possible.

4.6   References

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5. WATERSHED HYDROLOGIC SYSTEMS

5.1   Scope and Objectives

Optimization of real-time operation of a reservoir system is usually based upon forecasted inflows into each of the reservoirs. Releases through powerplants are scheduled in advance and are updated when new information on streamflow prediction becomes available. The daily streamflow forecast is generally made by a conceptual watershed model. A conceptual watershed model is a digital simulation model. A watershed is analyzed and expressed as a collection of mathematical terms and parameters, and the mathematical representations are improved and verified by simulating the response of the system with known input and output [Crawford and Linsley, 1969]. This is continued until the simulation model is judged to be an adequate representation of the physical system.

The objective of this study is 1) to characterize the parameters associated with a typical watershed model; 2) to identify the parameters that are amenable to remote sensing; and 3) to perform sensitivity analysis on the parameters with respect to streamflow prediction and to relate it via a decision-making model to hydropower production.

5.2   Hydrologic System

In recent years hydrologists have studied intensively various components of the hydrologic cycle, in order to understand the mechanics of the flow of water and to arrive at mathematical descriptions of the flow process. The hydrograph (streamflow vs time) of streamflow is the end product of the variable time and areal distributions of precipitation, evaporation and transpiration, physical characteristics of watersheds and soil moisture conditions. The two basic modes of approach with respect to the modeling of the hydrologic response of a watershed can be classified into the broad categories of physical hydrology and hydrologic systems investigation. Physical hydrology involves describing the mechanics of the flow processes by well-established physical laws. Such a model often involves solving nonlinear partial differential equations. The systems approach attempts to develop parametric models using field observations on input and output in the evaluation of the model parameters. Due to the

complexity of the physical processes involved and the non-homogeneity of the watershed itself, an all-physical model is impossible to solve; on the other hand, an all parameteric model is incapable of representing the response of such a system. As a compromise, simulation models attempt to combine physical laws with the parametric approach. Precipitation and potential evapotranspiration are the basic inputs for the model and actual evapotranspiration, streamflow, and soil moisture levels are generally obtained as outputs. The model attempts to establish continuous mathematical relationships among elements of the hydrologic cycle. Several lumped, empirical parameters in the model are optimized using historical input and output observations. Such a model is useful for daily streamflow prediction.

5.3   Some Typical Watershed Models

Several watershed models are reviewed, and input and model parameters are identified. The Generalized Streamflow Simulation System (GSSS) developed by the Sacramento River Forecast Center, and the Streamflow Synthesis and Reservoir Regulation (SSARR) Model developed by the U.S. Army Corps of Engineers, North Pacific Division, are selected to perform sensitivity analysis using data from an American River watershed in California and a Columbia River watershed.

5.3.1   The SSARR Model

The SSARR Model [1975] is a mathematical model of a river basin system for which streamflow can be synthesized by evaluating snowmelt and rainfall. The model has three basic components: a generalized watershed model, a river system model and a reservoir regulation model. When the configuration of all components of the system have been input to the computer, watershed routing is computed, followed by consecutive channel routing and combining until all operations are complete.

A schematic representation of the SSARR Model is shown in Figure 5-1. The characteristics are summarized below.
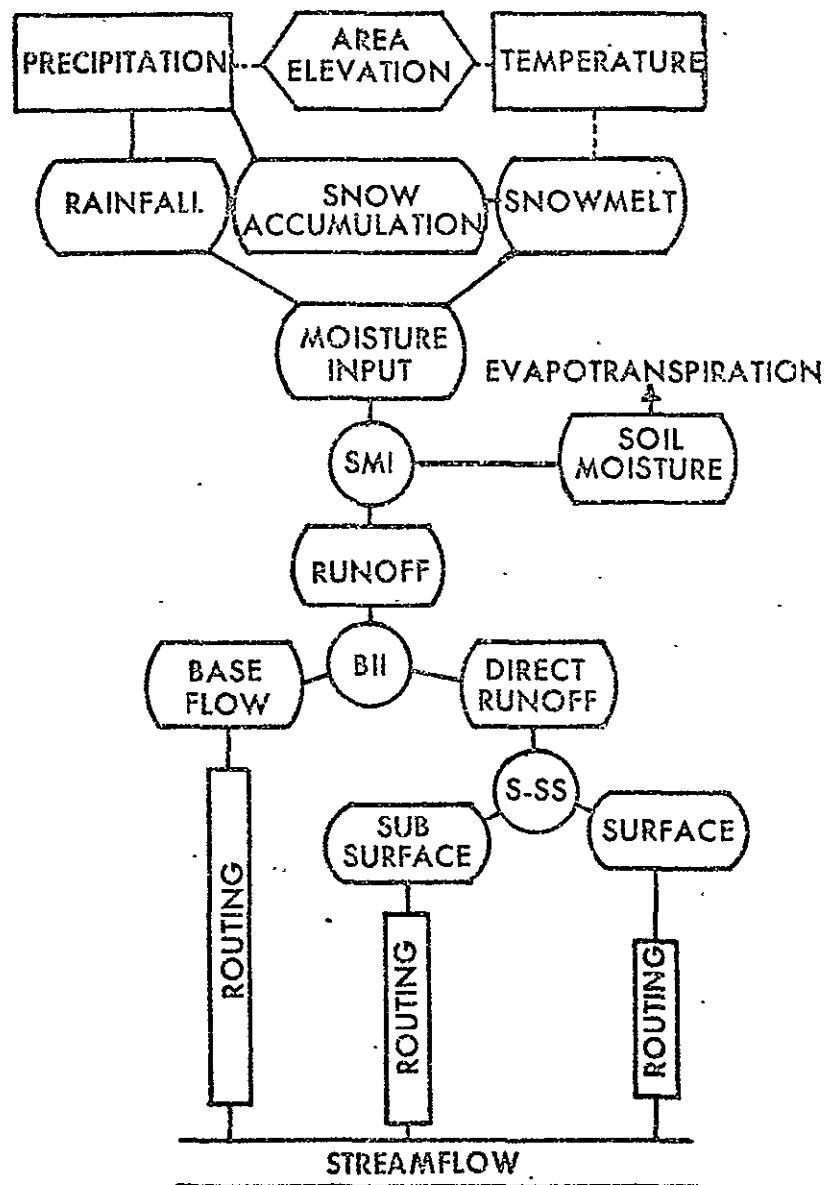
Figure 5-1. SSARR Watershed Model.

INPUT DATA:

1. Job Control and Time Control Data

2. Initial-Condition Data

   • Soil moisture index.

   • Baseflow infiltration index.

   • Flow in each increment of each channel reach.

   • Initial reservoir/lake elevation and outflows.

   • Phase values of the three routed runoff components (surface, subsurface, and baseflow).

   • Snowmelt initial condition such as melt rate and snow covered percent of area.

3. Precipitation Data

   • Rainfall data.

   • Station weighting factors.

4. Watershed Data

   • Daily evapotranspiration index (ETI).

   • A factor for reducing ETI on rainy day and/or when soil moisture becomes depleted.

   • Runoff percent — soil moisture index relationship.

   • Time delay or time of storage of base flow to calculate base flow infiltration index.

   • Surface — subsurface relationship.

   • Number of phases and time of storage per phase for each component of runoff.

5. Channel Reach Characteristics

   • Number of routing phases.

   • KTS and N values for calculations of time of storage T_s ($= KTS/Q^N$, where Q is discharge).

6. Lake/Reservoir Characteristics

- Reservoir regulation control data.

- Elevation-storage relationship for a lake.

- Elevation-discharge relationship for a free-flow lake.

- Backwater table for backwater computations.

- Maximum and minimum pool elevation.

7. Snowmelt Data

- (Option 1) — Temperature for the temperature index method.

- (Option 2) — Parameters for the generalized snowmelt equations.

- Miscellaneous data to evaluate the snowpack characteristics in a watershed.

8. System Configuration

ROUTING INTERVAL: Variable.

PROCESS SIMULATED:

Watershed Model:

1. Soil Moisture-Runoff Relationship: The percent of total rainfall input available for runoff is found from empirically derived relationships of soil moisture index (SMI) versus runoff percent (ROP). The SMI is depleted by the evapotranspiration index (ETI).

2. Base Flow: The portion of runoff that contributes to base flow is a function of the base flow infiltration index (BII). Time delay or time of storage of base flow is needed to calculate the BII.

3. Surface-Subsurface Flow Separation: The direct runoff is separated into surface and subsurface flow by empirically derived relationship.

4. Routing of Surface, Subsurface, and Base Flow: Each component of runoff to surface, subsurface base flow is routed through a specified number of increments of storage. These increments are considered as a series of small linear reservoirs which delay runoff.

5-5

5. Snowmelt: The calculation of snowmelt can be accomplished by either 1) temperature index approach or 2) the use of the generalized snowmelt equation for a partly forested area. In addition to methods of calculating snowmelt, two options are available to evaluate the snowpack characteristics in a watershed. The first option describes the snow covered area-runoff relationships of a watershed utilizing a snowcover depletion function. The second option provides the capability to subdivide a watershed into elevation bands of which are treated separately with respect to snow acculation and melt.

River System Model:

6. Channel Routing: It is accomplished through a series of linear reservoirs.

7. Lake Routing: It is based on free-flow conditions, i.e., elevation-outflow relationships are fixed and outflow is determined by hydraulic head. Routing is accomplished by an iteration solution of the continuity of a storage equation.

8. Reservoir Routing and Regulation: Routing through man-made reservoirs is determined by the same procedures used for natural lakes except that several controls can be exerted by the user.

9. Routing Streamflow-Backwater Model: River flows may be routed as a function of multivariable relationships involving backwater efforts from tides or reservoirs.

5.3.2 A Generalized Streamflow Simulation System (GSSS)

A Generalized Streamflow Simulation System [1973] is a conceputal system for modeling the headwater portion of the hydrologic cycle. It is based on a system of percolation, soil-moisture storage, drainage, and evapotranspiration characteristics. Each component of runoff (surface runoff, interflow, and base flow) is calculated using a concept of moisture accounting in upper zone tension water, upper zone free water, lower zone tension water, lower zone free water. A unit hydrograph (unitgraph) approach is used for direct, surface and interflow runoff. A provision is also made for the optimization of watershed parameters by inference from the rainfall and discharge records.

The basic components of the system are illustrated in Figure 5-2.
The characteristics of the model are:

INPUT DATA:

1. Job Control Data

2. Initial Moisture Conditions

   • UZTWC   — Upper zone tension water contents.

   • UZFWC   — Upper zone free water contents.

   • LZTWC   — Lower zone tension water contents.

   • LZFSC   — Lower zone supplemental free water contents.

   • LZFPC   — Lower zone primary free water contents.

3. Precipitation Data

   • Rainfall Data (including snowmelt).

   • RAWT   — Station Weights.

4. Evapotranspiration Data

   • ED   — Evapotranspiration demand.

   • PCTPN   — A set of twelve values for dimensioning mean
               daily evapotranspiration for each month.

5. Watershed Parameters

   • PCTIM   — The permanently impervious fraction of the basin
               contiguous with steam channels.

   • ADIMP   — Fraction of the basin which becomes impervious
               as all tension water requirements are met.

   • SARVA   — Fraction of the basin covered by streams, lakes,
               and riparian vegetation under normal
               circumstances.

   • UZTWM*   — The depth of water which must be filled over non-
               impervious areas before any water becomes
               available for free water storage.

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*Asterisk indicates that parameter is to be optimized.
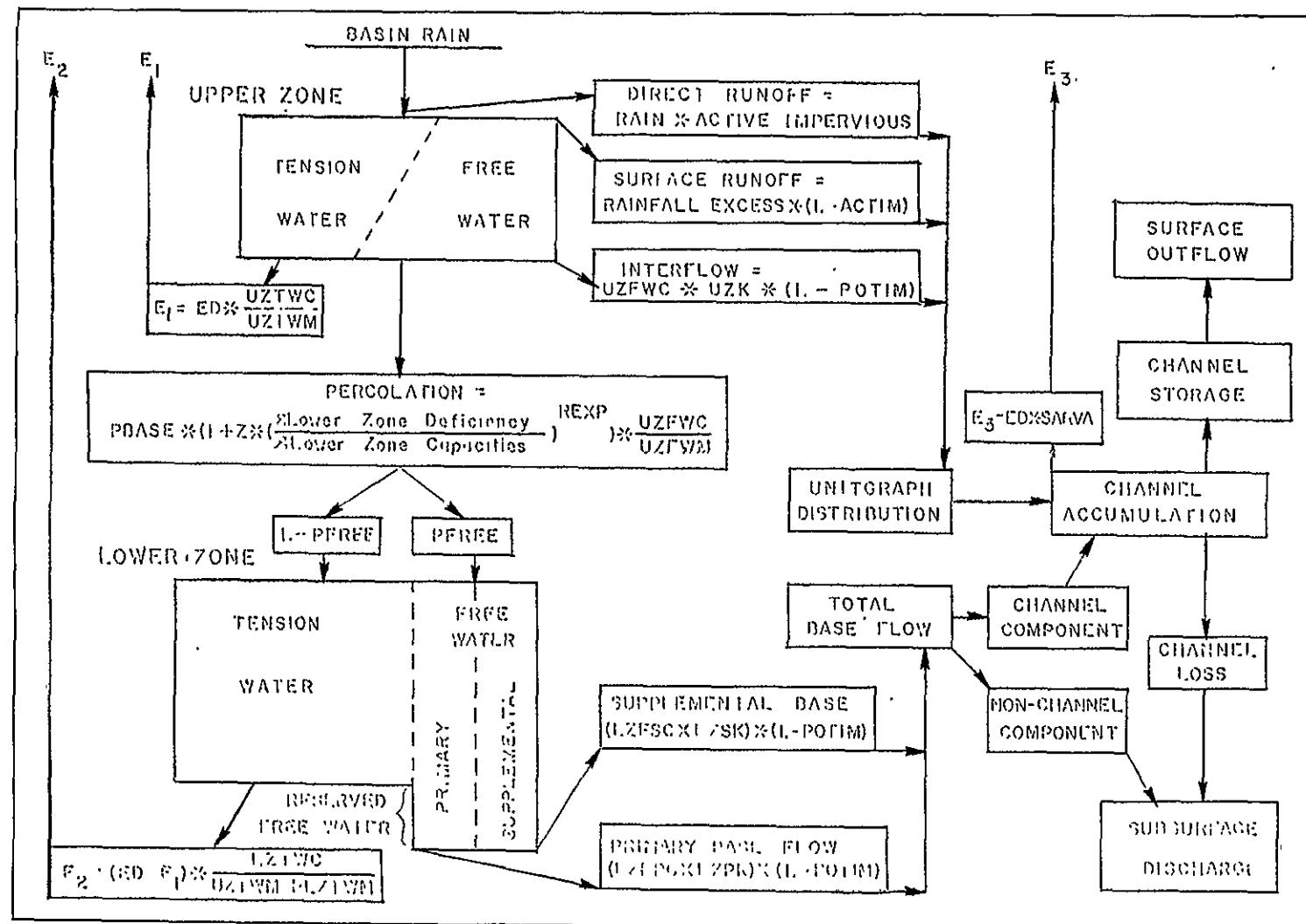
Figure 5-2. Components of a Generalized Hydrologic Model.

5. <u>Watershed Parameters (contd)</u>

- UZFWM* — The upper zone free water, representing that depth of water which must be filled over the non-impervious portion of the basin in excess of UZTWM in order to maintain a wetting front at maximum potential.

- UZK* — The upper zone lateral drainage rate expressed as the ration of the daily withdrawal to the available contents.

- PBASE — The saturated percolation rate when all aquifers are full.

- Z* — The percolation range coefficient representing the proportional increase in percolation from saturated to dry condition.

- REXP* — The exponent controlling the shape of the percolation curve.

- LZTWM* — The lower zone tension water maximum storage capacity.

- LZFSM* — The maximum capacity of lower zone supplemental free water.

- LZSK — Supplemental free water lateral drainage rate expressed as a fraction of supplemental free water contents.

- LZFPM* — The maximum capacity of lower zone primary free water storage.

  LZPK — Primary free water lateral drainage rate expressed as a fraction of primary free water contents.

- PFREE — The fraction of the percolated water which is transmitted directly to the lower zone free water aquifers.

_____

*Asterisk indicates that parameter is to be optimized.

5. Watershed Parameters (contd)

   - SIDE* — The portion of the base flow which is not observed in the stream channel.

   - SSOUT — The sub-surface outflow along the stream channel which must be provided by the stream before water is available for surface discharge.

6. Unitgraph

   - Non-dimentional unitgraph used for direct, surface and inter-flow runoff.

7. Channel Storage Characteristics

   - Volume of flow in each layer of a channel.

   - Muskingum routing coefficient for each layer.

ROUTING INTERVAL: Daily.

PROCESS SIMULATED:

1. Impervious Area: Rainfall occurring on a portion of the soil mantle covered by streams, lake surfaces, marshes, or other impervious area is directly linked to the streamflow network as direct runoff.

2. Surface Runoff: The permeable area that produces runoff when rainfall rate is sufficiently heavy so that it exceeds the percolation rate and the upper zone moisture demand.

3. Interflow: Interflow results from the lateral drainage of a upper zone free water storage.

4. Evapotranspiration: It is given as a function of a moisture content in the upper zone and lower zone tension water and a fraction of the basin covered by stream, lakes, and riparian vegetation.

5. Percolation: The percolation from the upper zone free water storage to the lower zone is controlled by the contents of the upper zone free water and the deficiency of lower zone moisture volume.

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*Asterisk indicates that parameter is to be optimized.

6. Base Flow: Base flow is the result of combining the drainage of two linear reservoirs; the primary and supplemental free water storage. The total base flow is divided into the channel and non-channel components.

7. Runoff: A unit hydrograph approach is used for direct, surface and interflow runoff.

8. Channel Storage: The channel storage future has provided for the places where significant changes in channel characteristics take place with changing depth of the flood wave. The channel storage mechanics are based upon a layered Muskingam concept.

9. Snowmelt: It is not included in the model. Snowmelt must be included in basin precipitation in the form of moisture available to the soil mantle.

Appendix A.1 summarizes all other models reviewed.

5.4 General Sensitivity Analysis

5.4.1 Approach

Sensitivity is the rate of change in one factor with respect to change in another factor [McCuen, 1973]. In watershed modeling, the variation of hydrograph for a given watershed depends upon the input and watershed parameters. Let h be the magnitude of the hydrograph, then h would depend upon the above-mentioned parameters. Let these parameters be p_1, p_2, ..., p_n, then

$$h = f(p_1, p_2, \ldots, p_n). \tag{1}$$

The general definition of sensitivity S_{p_i} with respect to a given parameter p_i [McCuen, 1973] is

$$S_{p_i} = \frac{\partial h}{\partial p_i} \approx \frac{\Delta h}{\Delta p_i} \approx \frac{f(p_i + \Delta p_i, p_j \mid j \neq i) - f(p_1, p_2, \ldots, p_n)}{\Delta p_i}, \tag{2}$$

where

$$f(p_i + \Delta p_i, \; p_j \big| j \neq i) = f(p_1, \; p_2, \; \ldots, \; p_n) + \frac{\partial f}{\partial p_i} \Delta p_i \; . \tag{3}$$

Since watershed models involve simulation, the direct method of differentiation in general is not possible, and the method of parameter perturbation is used to determine the sensitivity of the parameters. The method requires perturbing each parameter one at a time using a forward finite difference approximation. In order to determine the sensitivity of a n-parameter model, the model has to be solved (simulated) n independent times. Note that h is a function of time as watershed models are dynamic in nature. As a result, the sensitivity of parameters is also time dependent. The results from the sensitivity analysis can be used as a means of ranking the parameters in order of relative importance.

5.4.2 Computations

The Sacramento River Forecast Center Hydrologic Model (GSSS) was selected to perform the sensitivity analysis. Concurrent historical input (daily precipitation) and output (daily streamflow) measurements were obtained for the American River at Folsom Reservoir. The model was first calibrated using these measurements to determine the optimal values of the watershed parameters. The following 17 watershed parameters were involved in the model calibration:

<u>Watershed Parameters:</u>

p_1 = UZTWM = The depth of water which must be filled over non-impervious areas before any water becomes available for free water storage.

p_2 = UZFWM = The upper zone free water, representing that depth of water which must be filled over the non-impervious portion of the basin in excess of UZTWM in order to maintain a wetting front at maximum potential.

p_3 = LZTWM   = The lower zone tension water maximum storage capacity.

p_4 = LZFSM   = The maximum capacity of lower zone supplemental free water.

p_5 = LZFPM   = The maximum capacity of lower zone free water storage.

p_6 = UZK   = The upper zone lateral drainage rate expressed as the ration of the daily withdrawal to the available contents.

p_7 = LZSK   = Supplemental free water lateral drainage rate expressed as a fraction of supplemental free water contents.

p_8 = LZPK   = Primary free water lateral drainage rate expressed as a fraction of primary free water contents.

p_9 = Z or XPERC = The proportional increase in percolating from saturated to dry condition.

p_{10} = REXP   = The exponent controlling the shape of the percolation curve.

p_{11} = SIDE   = The portion of base flow which is not observed in the stream channel.

p_{12} = SSOUT   = The sub-surface outflow along the stream channel which must be provided by the stream before water is available for surface discharge.

p_{13} = PCTIM   = The permanently impervious fraction of the basin contiguous with stream channels.

p_{14} = SARVA   = Fraction of the basin covered by streams, lakes, and riparian vegetation under normal circumstances.

p_{15} = RSERV   = That fraction of the lower zone water which is unavailable for transpiration purposes.

P_{16} = ADIMP = Fraction of the basin which becomes impervious as all tension water requirements are met.

P_{17} = PFREE = The fraction of the percolated water which is transmitted directly to the lower zone free water aquifers.

The calibrated and optimized values of the parameters and the associated increments used in the finite difference approximation are listed as follows:

$$P_1 = 3.48 \qquad \Delta P_1 = 0.05 \, P_1$$

$$P_2 = 2.06 \qquad \Delta P_2 = 0.05 \, P_2$$

$$P_3 = 9.00 \qquad \Delta P_3 = 0.05 \, P_3$$

$$P_4 = 2.57 \qquad \Delta P_4 = 0.05 \, P_4$$

$$P_5 = 9.64 \qquad \Delta P_5 = 0.05 \, P_5$$

$$P_6 = 0.20 \qquad \Delta P_6 = 0.05 \, P_6$$

$$P_7 = 0.053 \qquad \Delta P_7 = 0.05 \, P_7$$

$$P_8 = 0.004 \qquad \Delta P_8 = 0.05 \, P_8$$

$$P_9 = 31.3 \qquad \Delta P_9 = 0.05 \, P_9$$

$$P_{10} = 0.92 \qquad \Delta P_{10} = 0.05 \, P_{10}$$

$$P_{11} = 0.28 \qquad \Delta P_{11} = 0.05 \, P_{11}$$

$$P_{12} = 0.00 \qquad \Delta P_{12} = 0.002$$

$$P_{13} = 0.03 \qquad \Delta P_{13} = 0.05 \, P_{13}$$

$$P_{14} = 0.05 \qquad \Delta P_{14} = 0.05 \, P_{14}$$

$$P_{15} = 0.23 \qquad \Delta P_{15} = 0.05 \, P_{15}$$

$$P_{16} = 0.009 \qquad \Delta P_{16} = 0.05 \, P_{16}$$

$$P_{17} = 0.30 \qquad \Delta P_{17} = 0.05 \, P_{17}$$

The sensitivity analysis was carried out for the 1957 calendar year. The sensitivity functions for the month of March for each of the above parameters are presented in Table 5-1. Parameter p_{15} turned out to be insignificant and therefore is not presented. Figure 5-3 shows the hydrograph of March 1957.

5.4.3 Sensitivity of Basin Precipitation

The sensitivity of the input function, basin precipitation, is presented by a sensitivity plot. The plot shows the sum of the squares of the errors when certain errors are introduced to the input function. The error is defined as the difference between the ordinates of hydrographs with and without noise. A uniform random noise was generated and the basin precipitation was corrupted by the generated noise. Figure 5-4 shows the effect of the input noise.

5.4.4 Covariance and Correlation Matrices

Using the results from the sensitivity analysis, the covariance and correlation matrices of the parameters are easily computed. The element a_{ij} of the covariance matrix A by definition is

$$a_{ij} = E\left[(p_i - \bar{p}_i)(p_j - \bar{p}_j)\right],$$

where $\bar{p}_i$ and $\bar{p}_j$ are the mean of parameters p_i and p_j and E represents the expectation.

If $h = f(p_1, p_2, \ldots, p_n)$ is normally distributed and the objective function used in the optimization of the watershed model is the least-squares, the covariance matrix A can be approximated by the inverse of the Hessian matrix, i.e.,

$$A = H^{-1},$$

where H is the Hessian matrix of h.

Table 5-1. Sensitivity Functions of Watershed Parameters.

No.	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{16}	P_{17}
1	-0.295	0.144	-0.371	0.114	-0.173	- 0.500	17.325	60.592	-0.009	0.478	-1.965	-1.001	1.443	0.000	1.024	-0.872
2	-0.273	0.079	-0.347	0.148	-0.157	- 0.395	17.000	71.125	-0.006	0.321	-1.782	-1.001	1.277	0.000	0.897	-0.802
3	-0.279	0.154	-0.346	0.070	-0.178	1.294	13.177	56.877	-0.011	0.513	-2.049	-1.001	2.460	0.000	1.941	-0.785
4	-0.333	0.438	-0.391	-0.198	-0.270	10.426	4.013	0.897	-0.028	1.271	-3.124	-1.001	21.844	0.000	19.540	-0.851
5	-0.453	1.641	-0.495	-0.693	-0.476	22.260	- 9.462	-109.511	-0.059	4.325	-5.426	-1.001	37.293	0.000	34.362	-1.030
6	-0.564	1.558	-0.596	-1.068	-0.684	20.764	-16.756	-198.541	-0.079	4.681	-7.610	-1.001	16.396	0.000	15.068	-1.199
7	-0.512	1.090	-0.549	-0.775	-0.628	6.775	- 5.021	-142.827	-0.060	3.654	-6.933	-1.001	0.345	0.000	0.036	-1.073
8	-0.432	1.524	-0.477	-0.437	-0.519	4.400	5.643	- 71.550	-0.039	4.425	-5.730	-1.001	4.671	0.000	4.273	-0.901
9	-0.396	0.846	-0.508	-0.519	-0.722	5.774	- 0.713	- 41.013	-0.048	2.856	-5.287	-1.001	7.202	0.000	6.731	-0.818
10	-0.347	0.432	-0.396	-0.124	-0.476	0.569	14.609	- 2.437	-0.020	1.759	-4.599	-1.001	- 1.352	0.000	- 1.464	-0.714
11	-0.281	0.149	-0.325	0.127	-0.325	- 1.298	21.027	49.367	-0.007	0.866	-3.570	-1.001	0.383	0.000	0.240	-0.581
12	-0.286	0.148	-0.330	0.049	-0.327	3.718	17.090	38.433	-0.009	0.903	-3.786	-1.001	5.731	0.000	5.402	-0.583
13	-0.284	0.141	-0.329	0.019	-0.329	1.338	15.611	35.224	-0.010	0.898	-3.886	-1.001	1.888	0.000	1.702	-0.575
14	-0.259	0.082	-0.304	0.083	-0.293	- 0.546	16.231	51.909	-0.007	0.677	-3.547	-1.001	- 2.917	0.000	- 2.761	-0.524
15	-0.250	0.070	-0.294	0.077	-0.284	1.459	14.733	54.536	-0.006	0.623	-3.478	-1.001	3.580	- 0.001	3.223	-0.503
16	-0.237	0.044	-0.279	0.100	-0.266	- 0.401	14.571	61.731	-0.005	0.521	-3.328	-1.001	0.761	0.000	0.615	-0.474
17	-0.218	0.020	-0.259	0.126	-0.241	- 1.918	13.640	71.101	-0.003	0.404	-3.091	-1.001	- 3.138	0.000	- 2.516	-0.437
18	-0.174	-0.111	-0.215	0.316	-0.165	- 2.411	18.922	114.031	0.005	-0.097	-2.275	-1.001	- 3.581	- 0.003	- 3.003	0.350
19	-0.206	-0.179	-0.206	0.346	-0.134	- 3.430	16.561	88.215	0.003	-0.369	-2.459	-1.001	- 3.491	- 0.005	- 2.927	-1.063
20	-0.165	-0.213	-0.181	0.393	-0.105	- 2.795	16.407	120.459	0.007	-0.516	-1.904	-1.001	- 1.418	- 0.007	- 2.787	-0.710
21	-0.095	-0.213	-0.152	0.434	-0.082	- 1.541	17.089	175.260	0.013	-0.441	-1.083	-1.001	- 2.202	0.000	- 2.528	0.116
22	-0.103	-0.205	-0.149	0.404	-0.077	- 1.728	14.037	164.471	0.011	-0.466	-1.168	-1.001	- 2.956	0.000	- 2.545	-0.067
23	-0.107	-0.196	-0.146	0.375	-0.072	- 1.805	11.188	156.946	0.010	-0.461	-1.212	-1.001	- 2.839	- 0.003	- 2.473	-0.174
24	-0.105	-0.188	-0.141	0.352	-0.067	- 1.760	8.912	155.163	0.009	-0.445	-1.180	-1.001	- 2.521	- 0.003	- 2.391	-0.191
25	-0.101	-0.180	-0.135	0.333	-0.061	- 1.683	6.938	154.925	0.009	-0.427	-1.129	-1.001	- 2.604	- 0.003	- 2.304	-0.183
26	-0.074	-0.165	-0.122	0.331	-0.052	- 1.188	6.163	172.507	0.011	-0.300	-0.833	-1.001	- 1.062	- 0.004	- 2.041	0.113
27	-0.066	-0.151	-0.116	0.315	-0.046	- 1.029	4.815	175.705	0.011	-0.251	-0.740	-1.001	0.169	0.000	- 0.093	0.184
28	-0.077	-0.069	-0.122	0.203	-0.068	0.119	0.383	153.041	0.006	-0.009	-1.048	-1.001	0.622	0.000	0.513	0.160
29	-0.099	0.057	-0.140	0.029	-0.111	2.567	- 4.645	112.267	-0.002	0.384	-1.675	-1.001	3.136	0.000	2.988	0.106
30	-0.122	0.170	-0.160	-0.129	-0.156	3.752	- 7.907	72.608	-0.003	0.753	-2.317	-1.001	5.478	0.000	5.277	0.063
31	-0.122	0.149	-0.159	-0.110	-0.155	1.118	- 5.332	71.683	-0.007	0.697	-2.360	-1.001	3.001	0.000	2.876	0.043

Note: $S_{P_{15}} = 0$.
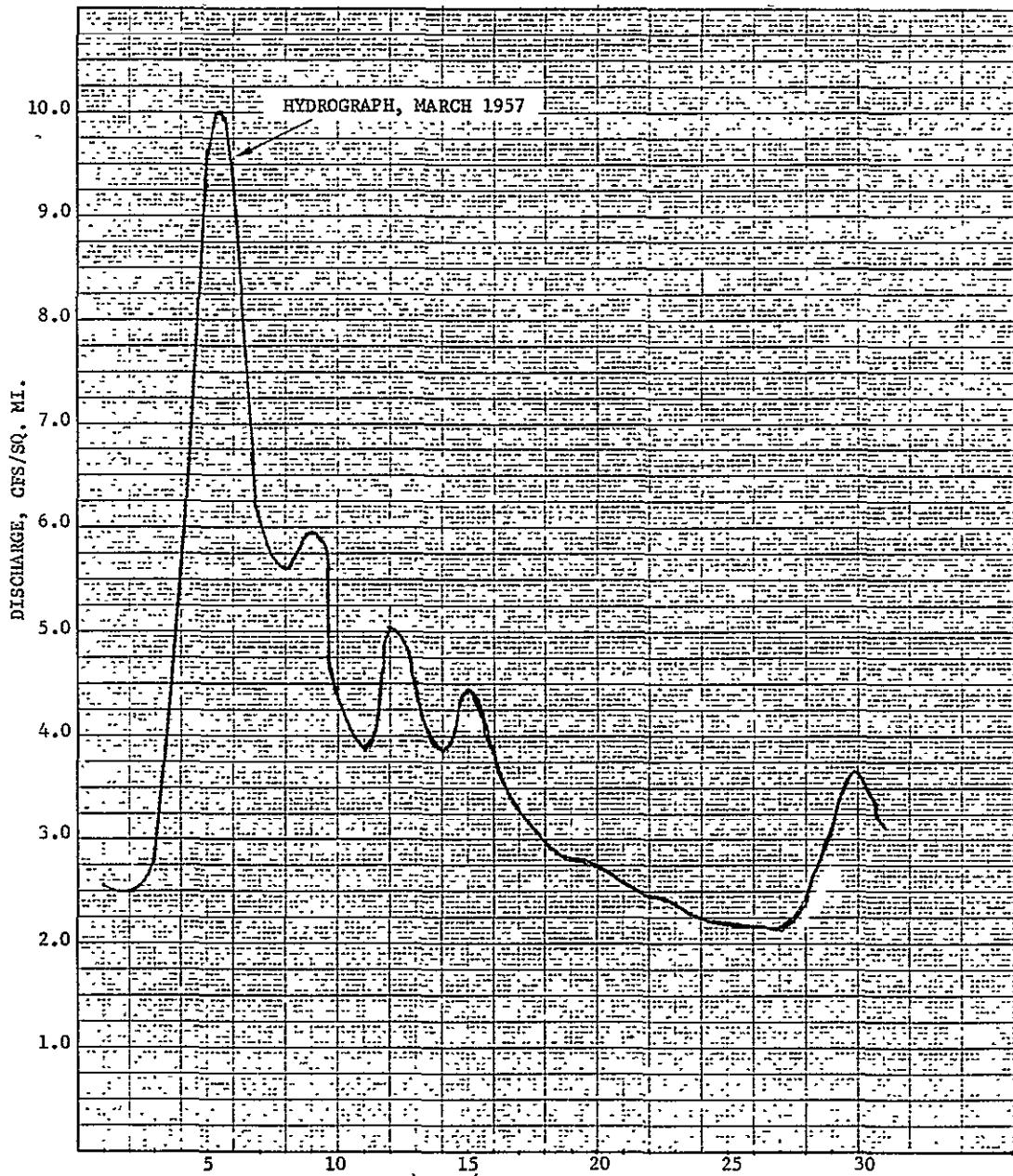
Figure 5-3. Hydrograph.
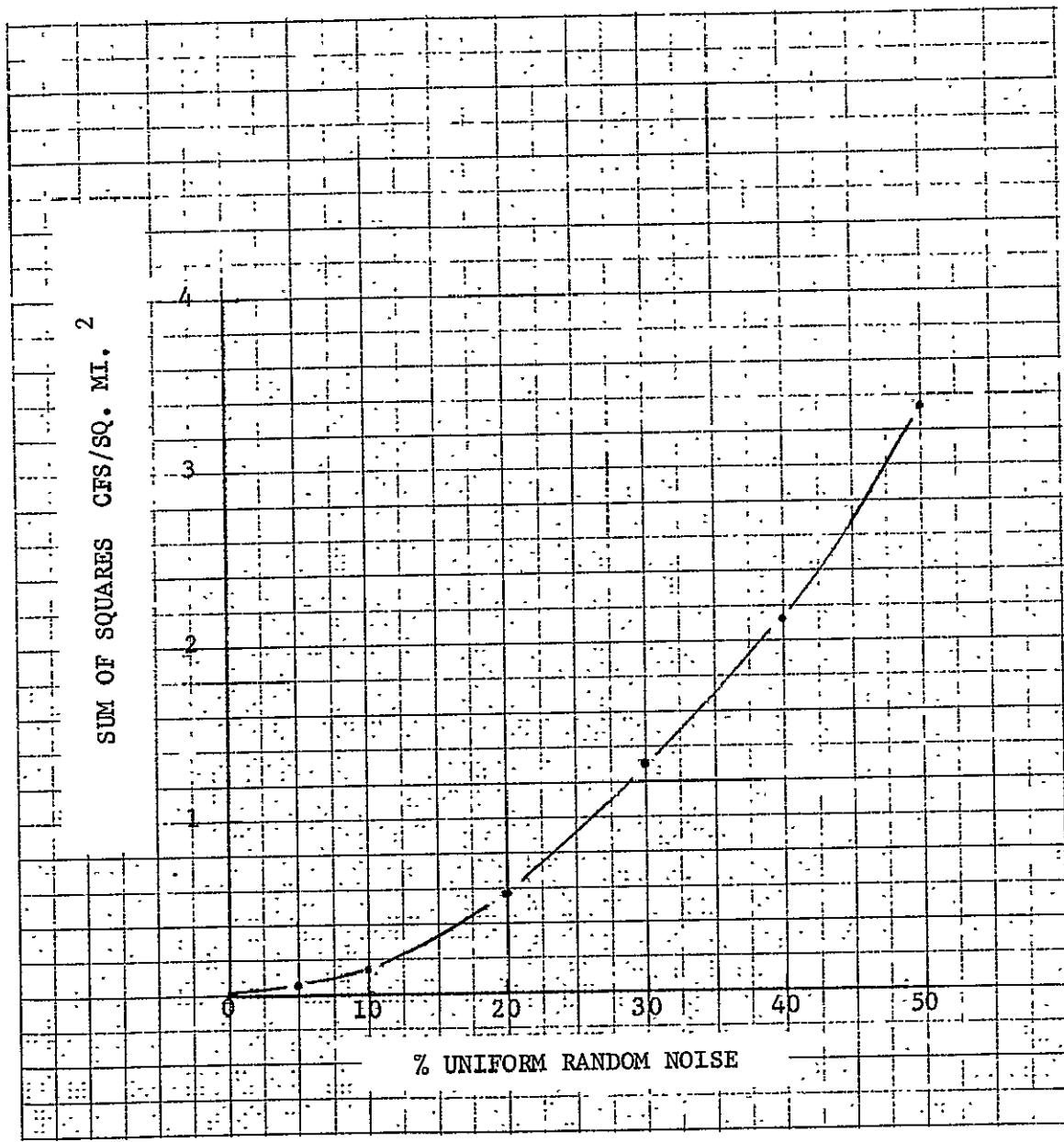
Figure 5-4. Sensitivity Plot.

By definition,

$$H = \begin{bmatrix} \dfrac{\partial^2 h}{\partial p_1^2} & \dfrac{\partial^2 h}{\partial p_1 \partial p_2} & \cdots & \dfrac{\partial^2 h}{\partial p_1 \partial p_n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \dfrac{\partial^2 h}{\partial p_n \partial p_1} & \cdots & & \dfrac{\partial^2 h}{\partial p_n^2} \end{bmatrix}$$

The Hessian matrix can be approximated using sensitivity coefficients,

$$H = \begin{bmatrix} \dfrac{\partial h}{\partial p_1}\dfrac{\partial h}{\partial p_1} & \dfrac{\partial h}{\partial p_1}\dfrac{\partial h}{\partial p_2} & \cdots & \dfrac{\partial h}{\partial p_1}\dfrac{\partial h}{\partial p_n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \dfrac{\partial h}{\partial p_n}\dfrac{\partial h}{\partial p_1} & \cdots & & \dfrac{\partial h}{\partial p_n}\dfrac{\partial h}{\partial p_n} \end{bmatrix},$$

where each element represents the summation over 31 days.

The covariance matrix A is easily obtained by inverting the above matrix.

$$A = H^{-1}.$$

The correlation matrix R is:

$$
R = \begin{bmatrix}
\dfrac{a_{11}}{\sqrt{a_{11} \cdot a_{11}}} & \dfrac{a_{12}}{\sqrt{a_{11} \cdot a_{22}}} & \cdots & \dfrac{a_{1n}}{\sqrt{a_{11} \cdot a_{nn}}} \\
\cdot & & & \cdot \\
\cdot & & & \cdot \\
\cdot & & & \cdot \\
\dfrac{a_{n1}}{\sqrt{a_{nn} \cdot a_{11}}} & \cdots\cdots\cdots & & \dfrac{a_{nn}}{\sqrt{a_{nn} \cdot a_{nn}}}
\end{bmatrix} ,
$$

where a_{ij}'s are elements of the covariance matrix.

The covariance and correlation matrices using the data of March, 1957, are presented in Tables 5-2 and 5-3. This information is useful with regard to model calibration, model optimization as well as model construction.

5.5 Sensitivity Analysis Using a Simple Performance Criterion

In order to be able to rank the relative importance of the parameters, a single performance criterion is used which is similar to the method described by Salomonsom, et. al. [1976].

5.5.1 Sensitivity of Watershed Parameters

The GSSS model was first calibrated using concurrent input and output measurements for the American River at Folsom Reservoir. The calibrated (optimized) values of the parameters are used as the reference values for the sensitivity analysis. For the given set of the optimized parameters, the hydrologic model was run for a period of one month and the resulting volume of streamflow above the maximum power release was obtained as the reference volume, V. The input and watershed parameters were perturbed one at a time to produce the sensitivity.

For each given parameter, the hydrologic model was run several times with this particular parameter varied from -50% to +50%, with all

Table 5-2. Covariance Matrix.

No.	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{16}	P_{17}
P_1	27360	-1790	-25480	15700	1183	13.03	-145.8	-46.48	-34710	829.0	-132.6	-2769	11.46	-3054	-24.23	1311
P_2	-1790	415.0	1342	-824.0	-240.6	-1.40	5.45	2.12	4970	-181.6	0.20	148.7	3.65	1596	-3.70	-22.45
P_3	-25480	1342	25060	-15700	-837.6	-8.53	152.1	46.61	27870	-625.7	130.0	2646	-9.09	4366	20.07	-1448
P_4	15700	-824.0	-15700	10660	183.7	4.16	-102.5	-32.09	-18880	383.8	-30.65	-1935	-5.00	-1894	-11.91	1054
P_5	1183	-240.6	-837.6	183.7	347.8	-0.06	-0.45	0.02	-3280	104.0	-29.83	49.44	-1.72	-897.4	2.22	-37.17
P_6	13.03	-1.40	-8.53	4.16	-0.06	-0.07	-0.03	-0.02	-1.46	0.70	-0.07	-1.46	0.02	6.72	-0.05	-0.19
P_7	-145.8	5.45	152.1	-102.5	0.45	-0.03	1.03	0.31	138.3	-2.61	0.44	17.69	-0.08	8.42	0.14	-10.49
P_8	-46.48	2.12	46.61	-32.09	0.02	-0.02	0.31	0.10	52.36	-1.00	0.03	6.13	-0.02	7.53	0.04	-3.27
P_9	-34710	4970	27870	-18880	-3280	-1.46	138.3	52.36	97630	-2179	56.52	3684	27.70	10200	-24.51	-1335
P_{10}	829.0	-181.6	-625.7	383.8	104.0	0.70	-2.61	-1.00	-2179	79.96	0.05	-70.71	-1.46	-648.9	1.41	11.16
P_{11}	-132.6	-0.20	130.0	-30.65	-29.83	-0.07	0.44	0.03	56.52	-0.05	5.77	-11.16	-0.41	-126.0	0.42	1.09
P_{12}	-2769	148.7	2646	-1935	49.44	-1.46	17.69	6.13	3684	-70.71	-11.16	428.1	-0.77	472.6	2.45	-198.1
P_{13}	11.46	3.65	-9.09	5.00	-1.72	0.02	-0.08	-0.02	27.70	-1.46	-0.41	-0.77	0.47	135.5	-0.53	-0.11
P_{14}	-3054	1596	4366	-1894	-897.4	6.72	8.42	7.53	10200	-648.9	-126.0	472.6	135.5	85810	-154.6	-611.8
P_{16}	-24.23	-3.70	20.07	-11.91	2.22	-0.05	0.14	0.04	-24.51	1.41	0.42	2.45	-0.53	-154.6	0.62	-0.36
P_{17}	1311	-22.45	-1448	1054	-37.17	-0.19	-10.49	-3.27	-1335	11.16	1.09	-198.1	-0.11	-611.8	-0.36	127.1

Table 5-3. Correlation Matrix.

No.	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{16}	P_{17}
P_1	1.00	-0.53	-0.97	0.92	0.38	0.31	-0.87	-0.90	-0.67	0.56	-0.33	-0.81	0.10	-0.06	-0.19	0.70
P_2	-0.53	1.00	0.42	-0.39	-0.63	-0.27	0.26	0.33	0.78	-1.00	-0.00	0.35	0.26	0.27	-0.23	-0.10
P_3	-0.97	0.42	1.00	-0.96	-0.28	-0.21	0.95	0.94	0.56	-0.44	0.34	0.81	-0.08	0.09	0.16	-0.81
P_4	0.92	-0.39	-0.96	1.00	-0.10	0.16	-0.98	-0.99	-0.59	0.42	-0.12	-0.91	0.07	-0.06	-0.15	0.91
P_5	0.38	-0.63	-0.28	-0.10	1.00	-0.01	-0.02	0.00	-0.56	0.62	-0.67	0.13	-0.13	-0.16	0.15	-0.18
P_6	0.31	-0.27	-0.21	0.16	-0.01	1.00	-0.11	-0.19	-0.02	0.30	0.12	-0.27	0.11	0.09	-0.25	-0.07
P_7	-0.87	0.26	0.95	-0.98	-0.02	-0.11	1.00	0.97	0.44	-0.29	0.18	0.84	-0.11	0.03	0.18	-0.92
P_8	-0.90	0.33	0.94	-0.99	-0.00	-0.19	0.97	1.00	0.53	-0.36	0.04	0.94	-0.07	0.08	0.16	-0.93
P_9	-0.67	0.78	0.56	-0.59	-0.56	-0.02	0.44	0.53	1.00	-0.78	0.08	0.57	0.13	0.11	-0.10	-0.38
P_{10}	0.56	-1.00	-0.44	0.42	0.62	0.30	-0.29	-0.36	-0.78	1.00	0.00	-0.38	-0.24	-0.25	0.20	0.11
P_{11}	-0.33	-0.00	0.34	-0.12	-0.67	0.12	0.18	0.04	0.08	0.00	1.00	-0.22	-0.25	-0.18	0.22	0.04
P_{12}	-0.81	0.35	0.81	-0.91	0.13	-0.27	0.84	0.94	0.57	-0.38	-0.22	1.00	-0.05	0.08	0.15	-0.85
P_{13}	0.10	0.26	-0.08	0.07	-0.13	0.11	-0.11	-0.07	0.13	-0.24	-0.25	-0.05	1.00	0.67	-0.99	-0.01
P_{14}	-0.06	0.27	0.09	-0.06	-0.16	0.09	0.03	0.08	0.11	-0.25	-0.18	0.08	0.67	1.00	-0.67	-0.19
P_{16}	-0.19	-0.23	0.16	-0.15	0.15	-0.25	0.18	0.16	-0.10	0.20	0.22	0.15	-0.99	-0.67	1.00	-0.04
P_{17}	0.70	-0.10	-0.81	0.91	-0.18	-0.07	-0.92	-0.93	-0.38	0.11	0.04	-0.85	-0.01	-0.19	-0.04	1.00

other parameters held at their reference values; the resulting V's were compared to the reference V. The difference between the reference V and the V obtained with an error introduced to the parameter is defined as ΔV. Table 5-4 shows the sensitivity results of the watershed parameters; Table 5-5 presents the sensitivity results of the input parameters and intial conditions. Figures 5-5 through 5-8 plot the results of Tables 5-4 and 5-5.

5.5.2 Sensitivity of Snowmelt Parameters

5.5.2.1 Snowmelt Model

It has been reported that the parameters which are more amenable to remote sensing are the ones associated with the snowmelt model. The Sacramento River Forecast Center Hydrologic Model does not contain a snowmelt model; the runoff produced by snowmelt is treated as an external input to the hydrologic model and is combined externally with rain to become the moisture input (MI) (or is imply referred to as precipitation) to the watershed. After a careful study, it appears that the snowmelt model of the SSARR model 1975 is most comprehensive and realistic, and contains most parameters of interest. Hence, the SSARR model was used to perform sensitivity analysis of the moisture input (MI).

Due to lack of data, it was not possible to calibrate the SSARR model, including snowmelt model, for the American River at Folsom Reservoir. However, data were obtained from the Corps of Engineers for the Columbia River system. The watershed designated as 33400000 of the Columbia River system was calibrated using historical concurrent input and output measurements. The sensitivity analysis described below concerns only the snowmelt model. The results obtained are then related to streamflow sensitivity via a watershed model. The assumption is made that the sensitivity will not change appreciably from watershed to watershed as long as both watersheds are subject to similar climatic conditions and the basic snowmelt characteristics are the same.

5.5.2.2 Runoff from Snowmelt Using SSARR Model

Snowmelt runoff poses complex problems to the hydrologist. Unlike rainfall, snowmelt is not generally measured quantitatively, but must be

Table 5-4. Sensitivity Results of the Watershed Parameters $(\Delta V/V)$ for March, 1957.

Parameters \ Error	-50%	-40%	-30%	-20%	-10%	0	10%	20%	30%	40%	50%
P_5	4.45	2.89	1.77	0.96	0.38	0	-0.22	-0.42	-0.54	-0.60	-0.65
P_3	2.59	1.84	1.24	0.74	0.35	0	-0.25	-0.45	-0.56	-0.60	-0.63
P_1	0.84	0.60	0.40	0.25	0.13	0	-0.09	-0.26	-0.40	-0.52	-0.62
P_9	0.78	0.57	0.40	0.26	0.12	0	-0.09	-0.17	-0.24	-0.30	-0.35
P_4	0.69	0.51	0.36	0.23	0.12	0	-0.08	-0.17	-0.23	-0.28	-0.32
P_6	-0.60	-0.48	-0.35	-0.23	-0.12	0	0.12	0.24	0.35	0.47	0.58
P_{10}	-0.59	-0.51	-0.39	-0.27	-0.13	0	0.17	0.33	0.49	0.65	0.82
P_2	-0.59	-0.46	-0.35	-0.23	-0.11	0	0.13	0.24	0.34	0.44	0.53
P_{11}	0.36	0.29	0.22	0.14	0.07	0	-0.05	-0.10	-0.14	-0.18	-0.22
P_{13}	-0.09	-0.07	-0.05	-0.04	-0.02	0	0.02	0.04	0.05	0.07	0.09
P_{16}	-0.03	-0.02	-0.02	-0.01	-0.01	0	0.01	0.01	0.02	0.02	0.03
P_8	-0.01	-0.01	-0.01	-0.00	-0.01	0	0.01	0.03	0.05	0.06	0.08

ΔV = Change of volume.

V = Total volume of water above the maximum power release = 15.7 cfs/sq. mi.

Watershed Area = 1875 sq. mi.

Results of P_7, P_{12}, P_{14}, and P_{15} are insignificant.

Table 5-5. Sensitivity Results of the Input Parameters and Initial Conditions (I. C.) $(\Delta V/V)$ for March 1957.

Variables \ Error	-50%	-40%	-30%	-20%	-10%	0	10%	20%	30%	40%	50%
Moisture Input (MI)	-0.91	-0.81	-0.70	-0.50	-0.25	0	0.41	0.84	1.42	2.06	2.90
$(I.C.)_3$	-0.70	-0.66	-0.61	-0.51	-0.28	0	0.38	0.81	1.35	2.00	2.76
$(I.C.)_5$	-0.65	-0.59	-0.51	-0.37	-0.19	0	0.29	0.60	1.02	1.50	2.07
$(I.C.)_1$	-0.62	-0.52	-0.40	-0.26	-0.09	0	0.13	0.24	0.40	0.60	0.84
$(I.C.)_4$	-0.25	-0.20	-0.15	-0.10	-0.05	0	0.06	0.12	0.19	0.25	0.31
Evapotranspiration (EVAP)	0.11	0.08	0.06	0.03	0.01	0	-0.01	-0.03	-0.04	-0.05	-0.04
$(I.C.)_2$	-0.01	-0.01	-0.00	-0.00	-0.00	0	0.00	0.00	0.01	0.01	0.01

$(I.C.)_1$ = UZTWC = upper zone tension water contents.

$(I.C.)_2$ = UZFWC = upper zone free water contents.

$(I.C.)_3$ = LZTWC = lower zone tension water contents.

$(I.C.)_4$ = LZFSC = lower zone supplementary free water contents.

$(I.C.)_5$ = LZFPC = lower zone primary free water contents.
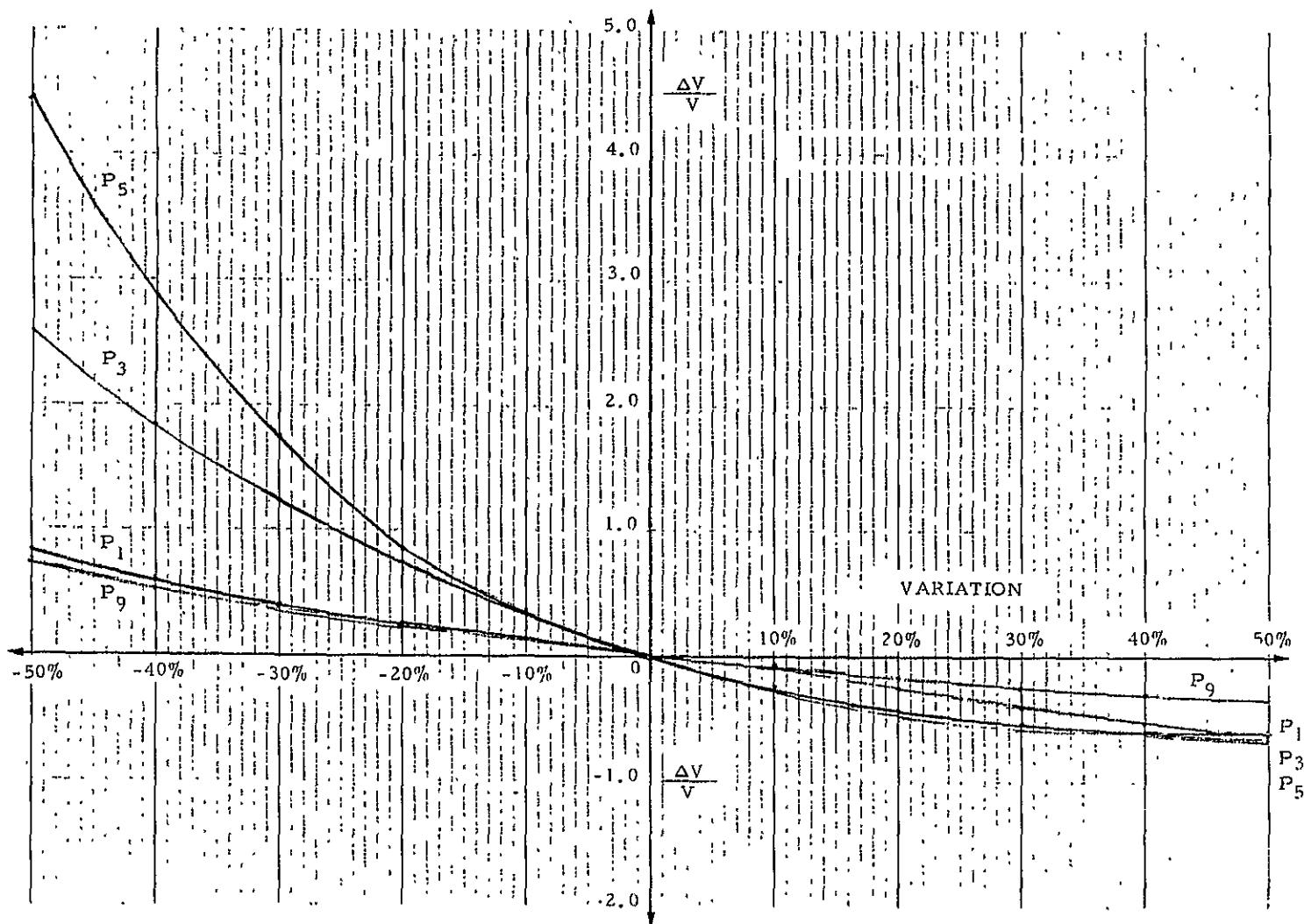
Figure 5-5. Sensitivity Results.
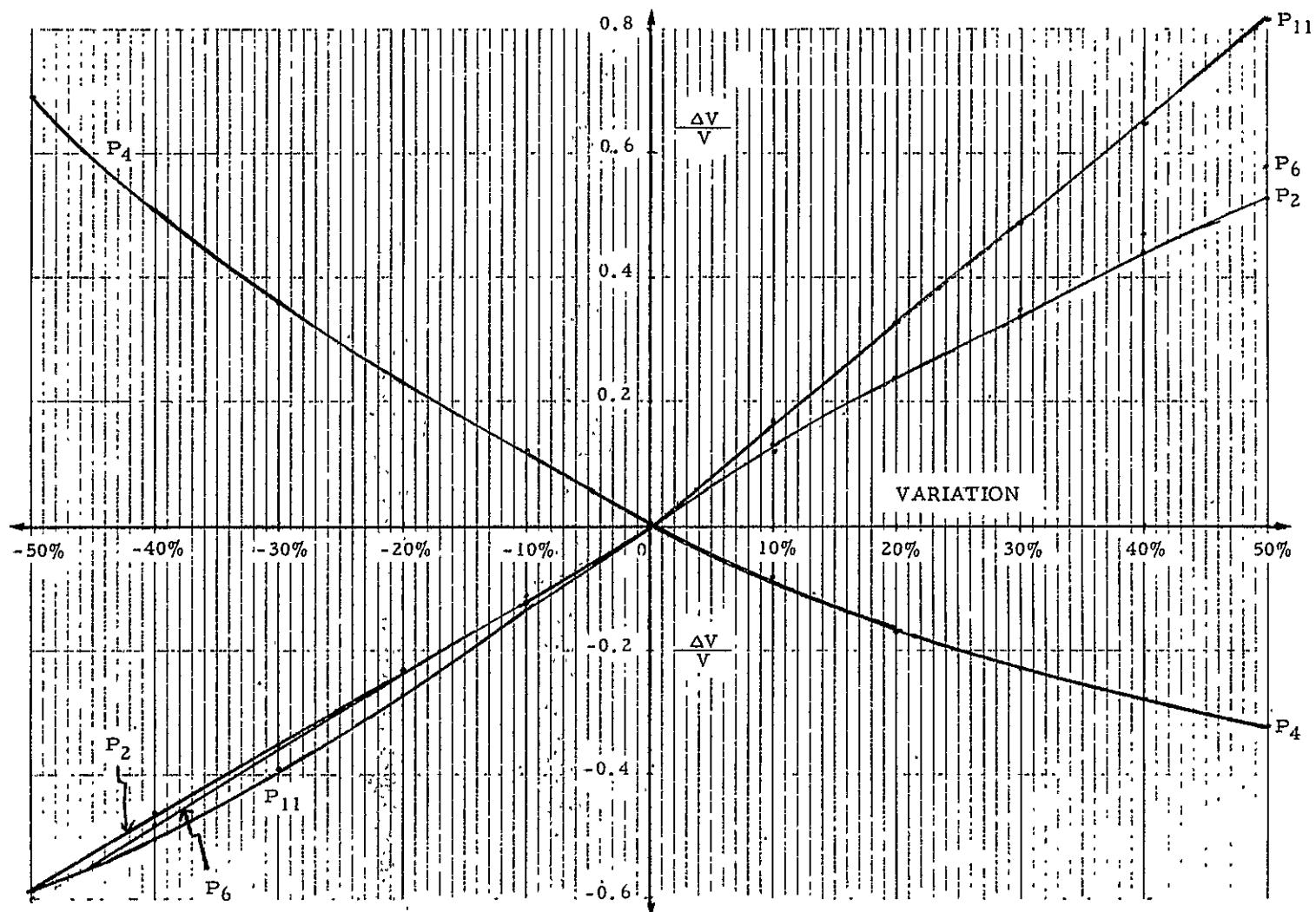
Figure 5-6. Sensitivity Results.
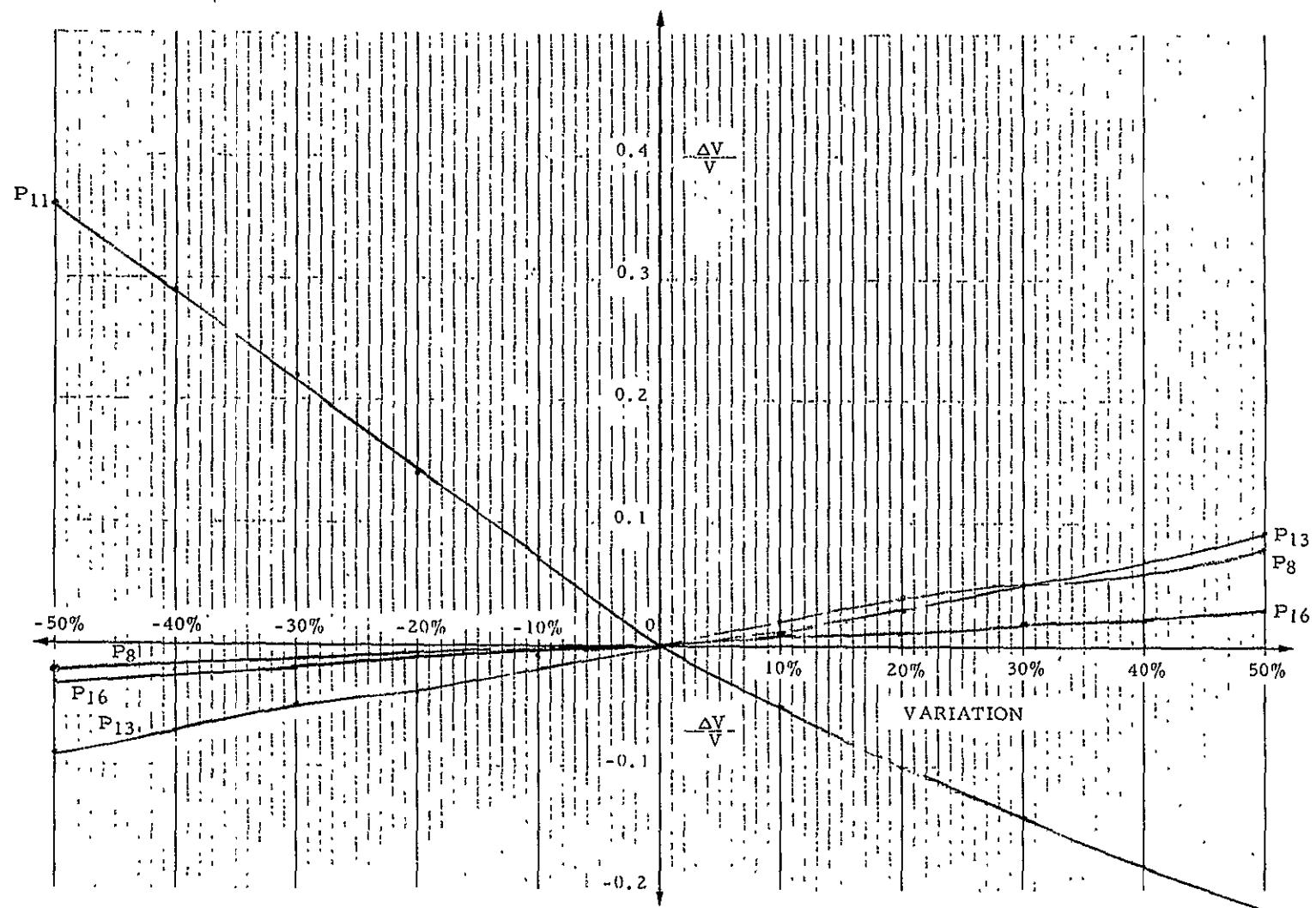
Figure 5-7. Sensitivity Results.
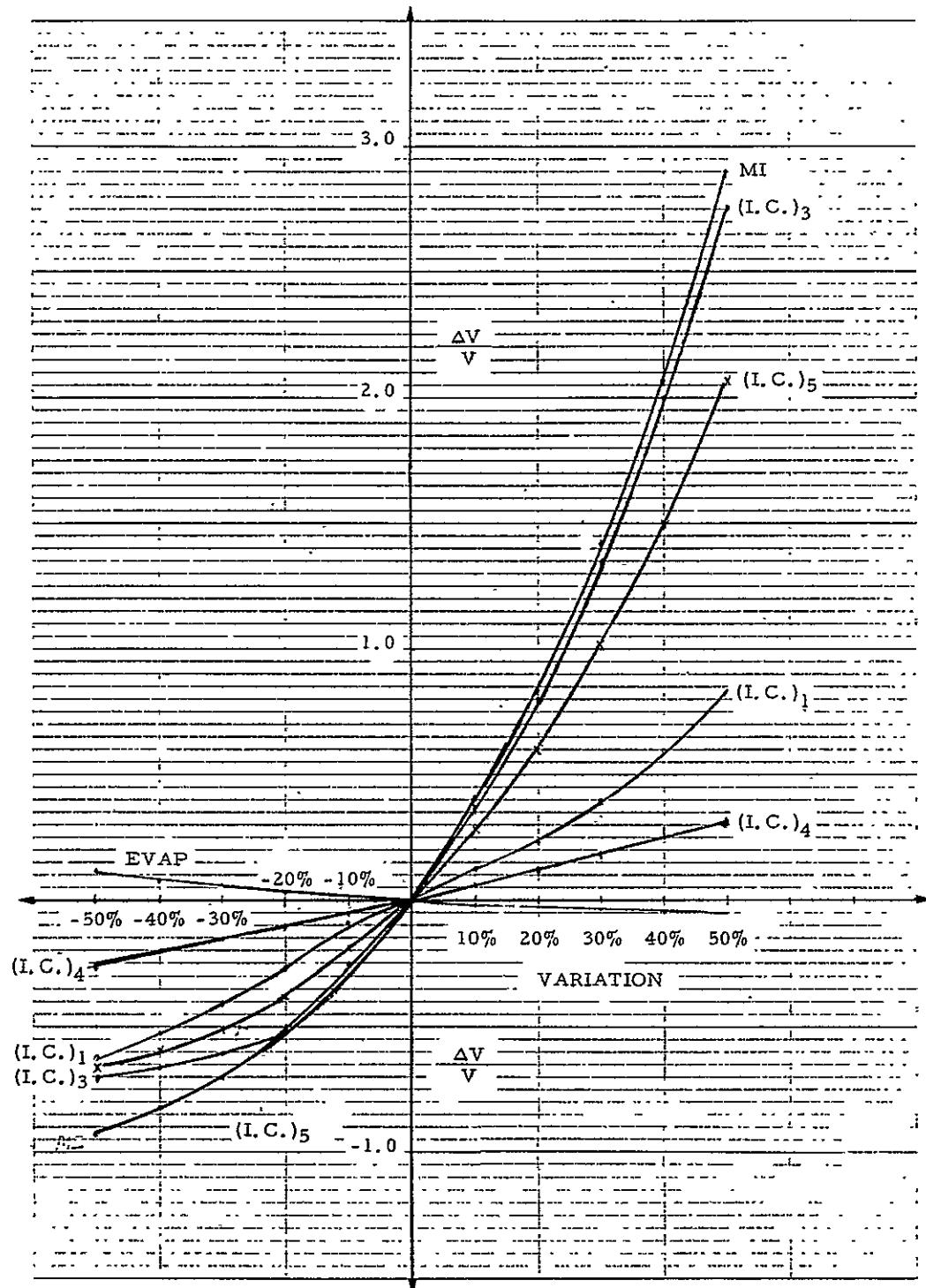
Figure 5-8. Sensitivity Results.

estimated indirectly from observations of meteorological parameters by a rational approach. The relationships between snow hydrology and flood hydrograph analysis are primarily determined by melt rates and the areal extent and water equivalent of the snowpack which are affected by terrain, vegetative cover, and climate. Snowmelt is a function of energy transfer to the snowpack. The natural sources of heat responsible for melting snow are:

1. Absorbed solar radiation
2. Net longwave radiation
3. Convective and advective transfer from the air
4. Latent heat of condensation from the air
5. Conduction of heat from the surrounding soil
6. Heat content of precipitation.

A generalized equation presented by the SSÁRR model lumps some of the above parameters into the following components of melt:

1. Shortwave radiation melt
2. Longwave radiation melt
3. Convection-condensation melt
4. Rain melt
5. Ground melt.

The equation used by the SSARR model is;

$$M = k'(1-F)(0.0040 \text{ Ii})(1-a) + k(0.0084\dot{v})(0.22 \text{ } T'_a + 0.78 \text{ } T'_d) + F(0.029 \text{ } T_a)$$

where

M = Snowmelt rate in inches per day

T'_a = Difference between the air temperature measured at 10 feet above the snow surface and the snow surface temperature in degrees Fahrenheit (°F); the snow surface temperature is assumed to be 32°F.

T'_d = Difference between the dewpoint temperature measured 10 feet above the surface of the snow and the temperature of the snow surface (32°F)

v = Wind velocity at 50 feet above the snow, in miles per hour

Ii = Solar radiation on a horizontal surface, in langleys

a = Average snow surface albedo expressed as a decimal

k′ = Basin shortwave radiation melt factor, expressed as a decimal

F = Average forest canopy cover, expressed as a decimal

k = Convection-condensation melt factor, expressed as a decimal.

The above equation is applicable only for partly forested areas. Melt equations for open or heavily forested areas could be programmed into the model if necessary.

To evaluate the snowpack characteristics in a watershed the SSARR model provides the following two options:

1. Snowcover Depletion. The snow covered area (%) is calculated by an empircal equation. The watershed can be treated as a 1) single watershed, or 2) split watershed — the watershed can be divided into two watersheds, the snow covered area and the snow free area with a different set of parameters for each of the areas.

2. Snow Band Option. With this option, a watershed is subdivided into one or more bands, or zones of relatively equal elevation. An inventory of snow accumulation and melt is maintained on each band. The approach is particularly suited for mountainous watersheds where snow depth increases with elevation.

5.5.2.3 Snowmelt Model and Input Parameters

A watershed located in the Columbia River system was selected for study. Physical characteristics and relevant data were provided by the U.S. Army Engineer Division, North Pacific, Portland, Oregon. Following are parameter and input descriptions:

1. Watershed area = 5580 sq. mi.

2. Simulation period: 4-11-68 to 5-10-68

3. Parameter definitions and values used to perform the sensitivity analysis:

P_1' = % of the snow covered area, 78.8%[*]

P_2' = Initial melt rate, 0.11 in./deg-day

P_3' = Initial accumulated runoff from rainfall, 0.0 in.

P_4' = Initial accumulated runoff from snowmelt, 2.12 in.

P_5' = Total seasonal snowmelt runoff, 10.0 in.

P_6' = Basin shortwave radiation melt factor, 0.9 decimal

P_7' = Convective-condensation melt factor, 0.6 decimal

P_8' = Effective forest cover ratio, 0.4

P_9' = Wind speed, 10 m.p.h. The wind speed may vary with time. For the purpose of sensitivity analysis a 10 m.p.h. wind is assumed due to lack of data.

P_{10}' = Rain freezing temperature, 38°F

P_{11}' = Base temperature for snowmelt, 40°F

P_{12}' = Air temperature lapse rate, 3.3°F/1000 ft.

P_{13}' = Precipitation, a function of time

P_{14}' = Air temperature, a function of time

P_{15}' = Dew point temperature. This value is a function of air temperature and humidity.

P_{16}' = Albedo ratio, 40% (can be varied with time)

P_{17}' = Insolation, 600 langleys (can be varied with time).

Using the reference values of the parameters, the snowmelt model was run for one month and the resulting moisture input (MI) was obtained as the reference MI. Each parameter was then varied independently from -50% to +50% to produce MI's. The difference between the reference MI and the MI's obtained with errors introduced to the parameter is defined as ΔMI. Table 5-6

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[*] Value is obtained from model calibration and is used as the reference value for sensitivity analysis.

Table 5-6. Sensitivity Results of the Input Parameters and Initial Conditions
Obtained from the SSARR Snowmelt Model.

$$\frac{\Delta MI}{MI}$$

Variables \ Error	-50%	-40%	-30%	-20%	-10%	0	10%	20%	30%	40%	50%
P'_1			-0.177	-0.108	-0.050	0	0.043	0.080	0.103	0.103	0.103
P'_{14}	-0.328	-0.208	-0.119	-0.059	-0.022	0	0.012	0.018	0.021	0.022	0.024
P'_{17}	-0.104	-0.070	-0.044	-0.025	-0.010	0	0.008	0.013	0.016	0.018	0.019
P'_{13}	-0.061	-0.049	-0.037	-0.024	-0.012	0	0.012	0.024	0.037	0.049	0.061
P'_{16}	0.017	0.015	0.013	0.009	0.005	0	-0.007	-0.015	-0.025	-0.037	-0.052
P'_8	0.012	0.010	0.008	0.006	0.003	0	-0.003	-0.007	-0.012	-0.017	-0.022
P'_9	0.012	0.010	0.008	0.005	0.003	0	-0.003	-0.006	-0.009	-0.012	-0.015

ΔMI = Change of moisture input.

MI = Moisture input to the watershed.

Watershed Area = 5580.0 sq. mi.

Simulation Period· April 11 to May 10, 1968.

shows the results of 8 parameters which are considered to be amenable to remote sensing; the results are plotted in Figure 5-9.

5.6   Summary of Sensitivity Results

Based upon the sensitivity analysis, the relative importance of the parameters can be determined. It should be noted that the sensitivities of most parameters are nonlinear, and that the sensitivity variations sometimes cross over, hence the ranking depends to some extent on the reference values. In addition, as pointed out by Salomonson [1976] one should use several years of data including many storms and watershed conditions for an ideal sensitivity analysis. The relative rankings for the GSSS Watershed Parameters, Input Parameters and Initial Conditions, and SSARR Snowmelt Parameters are given in Tables 5-7, 5-8 and 5-9, respectively.

5.7   Conclusions

Conceptual hydrologic models characteristically have input parameters such as precipitation and potential evapotranspiration; initial conditions such as upper zone tension water contents, upper zone free water contents, lower zone tension water contents, lower zone supplemental free water contents, and lower zone primary free water contents; and watershed parameters such as percent of impermeable area, channel roughness, etc. The initial conditions, input parameters and watershed parameters are critical factors affecting the accuracy of streamflow prediction. At the present time, initial conditions and parameters are expressed as single, lumped parameters. This will contribute a source of error in prediction since these parameters are distributed in nature. A watershed is usually nonhomogeneous. One way to minimize the error is to subdivide the watershed into several approximately homogeneous sub-regions; each sub-region is then associated with a set of its own parameters. The sub-regions are connected by continuity equations. This approach requires considerably more information on initial conditions and input parameters, and more observations are required before implementing a watershed model. As pointed out before, the precipitation includes rain and snowmelt. In order to provide the watershed model with spatially varied input, more rain gages and a better snowmelt model are needed. The watershed model should also be capable of receiving the spatially varied input.

5-34
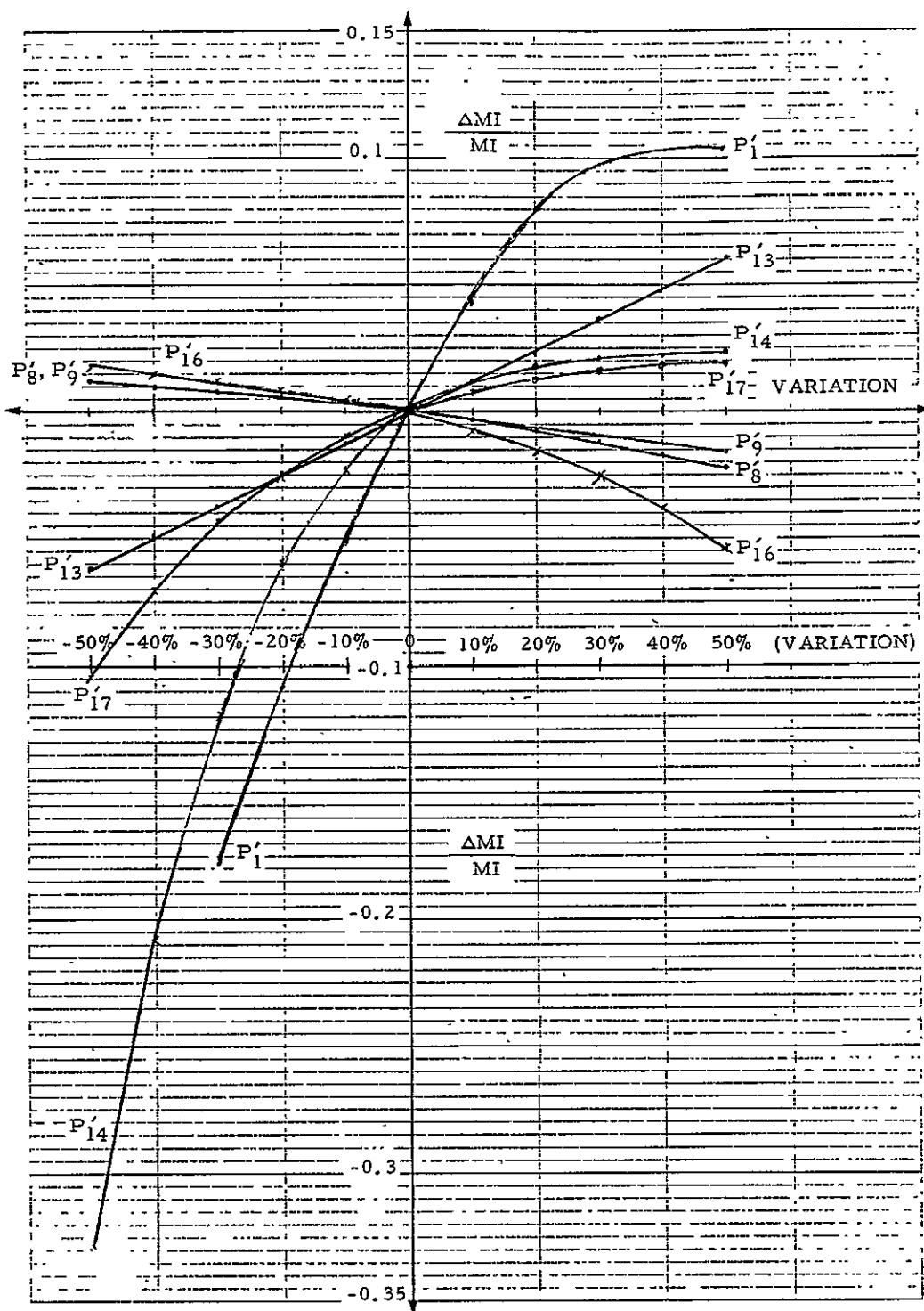
Figure 5-9. Sensitivity Results.

Table 5-7. Sensitivity Analysis ($\Delta V/V$).

Ranking	Watershed Parameters (GSSS)	% Change in Streamflow / % Change in Parameters
1	P_5, Lower Zone Free Water Storage Capacity	-3.8
2	P_3, Lower Zone Tension Water Storage Capacity	-3.5
3	P_1, Depth of Water to Fill the Non-Impervious Area	-1.3
4	P_9, Percolation	-1.2
5	P_4, Lower Zone Supplemental Free Water Capacity	-1.2
6	P_6, Upper Zone Lateral Drainage Rate	1.2
7	P_{10}, Shape Factor for Percolation	1.2
8	P_{12}, Upper Zone Free Water	1.1
9	P_{11}, Base Flow	-0.7
10[*]	P_{13}, Permanently Impervious Fraction of the Basin	0.2
11	P_{16}, Fraction of the Basin Which Become Impervious	0.1
12	P_8, Lower Zone Lateral Drainage Rate	0.1

[*]Amenable to remote sensing.

Table 5-8. Sensitivity Analysis ($\Delta V/V$).

Ranking	Input Parameters and Initial Conditions	$\dfrac{\%\ \text{Change in Streamflow}}{\%\ \text{Change in Parameters}}$
1	MI, Moisture Input (Precip + Snowmelt[*]), MI	4.0
2	I.C.3, Lower Zone Tension Water Contents	3.8
3	I.C.5, Lower Zone Primary Free Water Contents	2.9
4[*]	I.C.1, Upper Zone Tension Water	1.3
5	I.C.4, Lower Zone Supplementary Free Water	0.60
6	Evapotranspiration	-0.10
7	I.C.2, Upper Zone Free Water	0.00

[*]Amenable to remote sensing.

Table 5-9. Sensitivity Analysis ($\Delta MI/MI$).

Ranking	Snowmelt Parameters	$\dfrac{\% \text{ Change in Melt Rate}}{\% \text{ Change in Parameters}}$
1*	P_1, Snow Covered Area	-0.5
2	P_{14}, Air Temperature	-0.2
3	P_{17}, Insolation	-0.1
4	P_{13}, Precipitation	-0.1
5	P_{16}, Albedo	0.05
6*	P_8, Effective Forest Cover Ratio	0.03
7	P_9, Wind Speed	0.03

*Amenable to remote sensing.

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6. REVIEW OF WEATHER FORECAST TECHNIQUES

6.1 Introduction

There appears to be no universal agreement on the definitions of terms to describe the period covered by a forecast. In general, the period is classified by 1) short-range 2) intermediate-range and 3) long-range. A short-range forecast usually covers up to five days, an intermediate-range forecast covers up to two weeks, and a long-range forecast covers beyond two weeks up to a season·or a year. There are two classifications with regard to the types of models used for weather forecasting. They are statistical and physical models.

The statistical model ignores physical dynamics and uses historical concurrent measurements on dependent variables and several independent variables. Regression equations are derived by standard statistical means. Such a model in general can not predict time variation and is used more frequently for long-range forecast, for example the seasonal volumetric precipitation of a watershed.

The physical approach utilizes the physical laws which governs the complex dynamics of the atmosphere. The laws include thermodynamic equations, equations of motion, the equation of state, and the equation of continuity of mass. The model is characterized by a set of nonlinear partial differential equations. With the specification of appropriate initial and boundary conditions, solutions can be obtained by finite-difference approximations utilizing high speed computers. Such a model is suitable for short-range forecasts but is very questionable for intermediate or long-range forecasts. Since only small errors in observation or calculation can render the predictions inaccurate, the accuracy of solutions deteriorates after three or four days.

Recently, some approaches combine statistical with physical models. The Model Output Statistics (MOS) technique developed by the Techniques Development Laboratory, National Weather Service, National Oceanic and Atmospheric Administration (NOAA) [Glahn and Lowry, 1972 and Bermowitz, 1975] is an example.

6.2   Model Output Statistics (MOS)

Model Output Statistics technique is an objective weather forecasting technique which consists of determining a statistical relationship between a predictive and variables forecast by a numerical model (physical model) at some projection time (times) [Glahn and Lowry, 1972]. The MOS method involves matching observations of local weather with output from numerical models. Forecast equations are then derived by statistical techniques such as screening regression, regression estimation of event probabilities, and the logistic model. In this way the bias the inaccuracy of the numerical model, as well as the local climatology, can be built into the forecast system. The MOS project is being carried out by the Techniques Development Laboratory, National Weather Service, NOAA and is illustrated by schematic form in Figure 6-1.

The definitions of symbols are as follows:

1.   Type of Model

SAM	=	Subsynoptic Advection Model
PE	=	Primitive Equation Model
TRAJ	=	Trajectory Model
LFM	=	Limited Area Fine Mesh Model
SUM	=	Sum Model of Grayson and Bermowitz
BLM	=	Boundary Layer Model

2.   Output Variables

POP	=	Probability of Precipitation
POFP(P)	=	Conditional Probability of Frozen Precipitation
TEMPS	=	Temperature, e.g., Maximum Temperature
WINDS	=	Surface Wind
CLOUDS	=	Cloud Amount
SHOWERS		
S. STORMS	=	Thunderstorms
CEILING		
VISIBILITY		
QPF	=	Quantitative Precipitation
FOG		
DEW POINT		

MODEL OUTPUT STATISTICS (MOS)
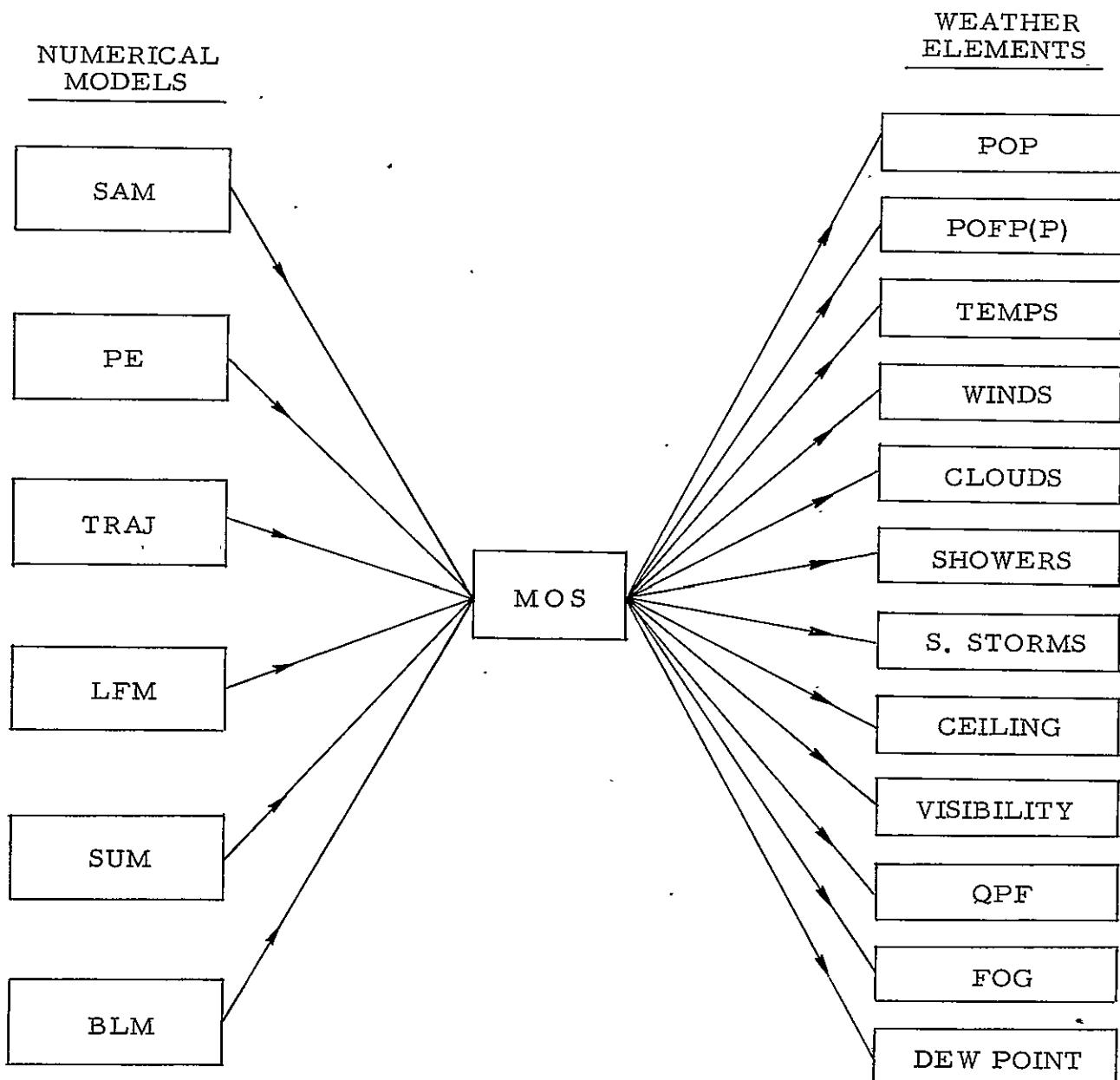
Figure 6-1. The MOS Program in Schematic Form.

Output from the operational numerical models on the left can be processed
by complex combination of computer programs in the middle to produce
automated forecasts of any weater element on the right.
(After Klein and Glahn, 1974.

At the present time, MOS has been successfully applied to SAM, PE and trajectory models.*

Bermowitz, et. al. (1976) have applied MOS to the Columbia River Basin. Regression equations are developed for forecasting warm season precipitation and temperature. They concluded that greater detail in precipitation amount and max/mix temperature forecasts will lead to improved streamflow forecasts in the Columbia River Basin and, therefore, to improved scheduling of the power operation of the Federal Columbia River System. Daily streamflow predictions are presently made by the Streamflow Synthesis and Reservoir Regulation (SSARR) Model for operational use for the Columbia River System. The model requires forecasted precipitation, temperature and other variables to be used as input parameters. With more accurate weather forecasts, the predicted streamflows will undoubtedly be more reliable. It is believed that MOS can forecast precipitation and temperature up to four days in advance and therefore can give sufficient lead time in streamflow predictions to allow more efficient scheduling of water releases for hydropower production, flood control and other objectives than is presently possible. A sample equation developed by Bermowitz, et al. (1976) for todays's maximum temperature is illustrated in Table 6-1.

The prediction equation has the following form,

$$\hat{Y} = a_o + a_1 x_1 + a_2 x_2 + \ldots + a_k x_k$$

The carat indicates an estimate, and the a_i's are the regression constant and coefficients. The a_i's are determined such that the sum of the squares of the estimation errors is a minimum on the dependent sample of size n, i.e.,

$$\sum_{j=1}^{n} (y_j - \hat{y}_j)^2 = \min .$$

---

*Note that surveying and documenting of the numerical prediction models in use at significant operational and research centers worldwide are being carried out by Ocean Data Systems, Inc. (ODSI), Monterey, California.

Table 6-1. Sample Temperature Equation for Today's max at Mt. Fanny, Oregon. A 5-point smoothed field is denoted by *. The total reduction of variance is given below the equation. (After Bermowitz et al., 1976).

Predictor	Valid Time (hr after 0000 GMT)	Units	Constant and Coefficients
PE 850-mb Temp	12	°K	1.852
PE 850-mb Temp	24	°K	1.423
Sine 2xDay of Yr	—	—	2.090
Cosine Day of Yr	—	—	− 2.880
PE SFC TO 490-mb Mean RH*	24	%	− .119
PE 500-1000-mb Thickness	12	m	.057
TRAJ 850-mb 24-Hr Net Vert Disp	24	.mb	.039
PE 850-mb U Wind	24	m/sec	− .408
PE 500-mb Temp minus PE 850-mb Temp	24	°K	− .421
PE Prec Water*	30	kg/m^2	.288
Constant	—	°F	−398.900

TOTAL REDUCTION OF VARIANCE = .943.

A measure of the goodness of the equation for estimating Y is the reduction of variance RV, where

$$RV = \frac{\frac{1}{n} \sum_{j=1}^{n} (y_j - \bar{y})^2 - \frac{1}{n} \sum_{j=1}^{n} (y_j - \hat{y}_j)^2}{\frac{1}{n} \sum_{j=1}^{n} (y_j - \bar{y})^2},$$

where $\bar{y}$ is the sample mean.

In Table 6-1, column 1 consists of the x_j's and column 4 consists of the a_i's. Concurrent historical local observations and solutions from PE and TRAJ models were used in the development of the regression equation. The accuracy in predicting max-min temperatures with the regression equations of Table 6-1 are shown in Table 6-2 for a range of forecast periods. The standard errors are relatively small through the third and fourth days, making the technique useful in predicting snowmelt during the peak runoff season. The potential improvement in inflow forecasting using the MOS technique has not been analyzed, but should be examined in subsequent studies. A similar summary of precipitation prediction accuracy is shown in Table 6-3 for several regions in the Columbia River basin. The accuracies tend to decrease with increasing prediction period, and with increasing amounts of precipitation. Although these accuracies represent an improvement over those obtained by conventional forecasting techniques, the levels of accuracy are not adequate for improving inflow predictions significantly. Further analyses should be conducted to determine the impact of MOS techniques on inflow anticipation times and accuracies, using the full-range of weather element variables given in Figure 6-1.

6.3   JPL Studies on the Impact of SEASAT Data on Short-Term Weather
       Forecasting

Analyses are being carried out at JPL on the potential use of SEASAT data for a better initialization of a numerical model. It is believed that the satellite's capabilities to measure winds at the sea surface along with, possibly, temperature profiles can create useful update information for short-

Table 6-2. MOS — Temp Prediction.

Forecast	Reduction of Variance (%)	Standard Error (°F)
0000 GMT		
Today's Max	89	3.9
Tonight's Min	80	3.8
Tomorrow's Max	84	4.9
Tomorrow Night's Min	74	4.1
Third Day's Max	76	5.8
Fourth Day's Min	69	4.6
Fourth Day's Max	68	6.7
1200 GMT		
Tonights's Min	83	3.6
Tomorrow's Max	87	4.4
Tomorrow's Min	78	4.1
Third Day's Max	80	5.5

Table 6-3. MOS — Prediction of Precip Amount.

Projection (hr)	Category (inch)		
	≥ .25	≥ .50	≥ 1.0
0000 GMT			
0-24	.215	.142	.095*
24-48	.144	.095	.067*
48-72	.125	.089	.144**
72-96	.097	.066	.083**
1200 GMT			
12-36	.172	.107	.080*
36-60	.115	.071	.039*

*Regions 1, 2, 3, and 6 only.
**Regions 1 and 3 only.

range forecasts [JPL, 1975]. The improvement in numerical forecasting can best be understood through the study of the errors which cause the forecasts to fail in the short range. These errors can be classified in three major groups: 1) misrepresentation of the physics, 2) initialization error, and 3) truncation error. Initialization of a numerical model requires frequent updating. Initial conditions must be provided to the partial differential equations before solutions can be made. The data that are available at present on a daily basis are both inbalanced and insufficient for the initial conditions required by almost all numerical models. As pointed out by the JPL studies this is because a) there are not enough observations taken over the globe, especially over the oceans, and b) the numerical schemes which solve the equations in the models are sensitive to the kind of data they can handle. Data collected from SEASAT will provide additional observations. By remote sensing, many areas of the oceans and continents can be included in the meteorolical data network.

Analyses to date of the potential contributions of better surface wind data from SEASAT measurements, have not shown overall improvements in weather forecasting accuracy. It appears that the variances of wind vector measurements are "damped" out by the PE model, hence, reductions in the variances do not improve the accuracy of the model. Further analyses are addressing the potential improvements attainable through reductions in the biases of measurements.

6.4 References

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7. SYNOPTIC SNOWMELT MODELS

7.1   Introduction

Experience has shown that reliable formulas for forecasting seasonal as well as short-term runoff can be obtained by regression and correlation analysis. Reliable forecasting is necessary to plan reservoir operations so as to maximize project accomplishments. A thorough examination of the meteorological variables and the snowmelt process is needed to improve the runoff forecast resulting from snowmelt. Independent variables used in the development of regression equations include snow water content, precipitation index, previous streamflow, snow-cover depletion, wind, air temperature, vapor pressure and net radiation.

7.2   Some Typical Models

Zuzel and Cox [1975] used factor analysis and regression analysis to determine the effectiveness of wind, air temperature, vapor pressure and net radiation in predicting snowmelt rates. Using meteorological and snowmelt data collected at a site near Boise in May 1976, Zuzel and Cox [1975] have shown that the standard error of daily snowmelt prediction could be decreased 13% by using vapor pressure, net radiation, and wind in predictive equations rather than air temperature alone. Table 7-1 shows meteorological variable combinations in relation to snowmelt for daily melt. None of the variables is amenable to measurement from air/spaceborne sensors.

Leaf [1975] described a procedure whereby the correlation between satellite-derived snow-cover depletion and residual snowpack water equivalent, can be used to update computerized residual flow forecasts for the Conejos River in Southern Colorado. Satellite snow cover data was introduced into the Subalpine Water Balance Model [Leaf and Brink, 1973] to provide a sound physical basis for making continuous short-term streamflow forecasts in the Upper Rio Grande Basin. Reconstitution studies of a 15-year streamflow record made by Leaf [1975] indicate that the model is adequate for making residual volume forecasts at time intervals as short as 10 days. Figure 7-1 shows the simulated and observed results.

Table 7-1. Meteorological Variable Combinations
in Relation to Snowmelt.

Independent Variables	R	Standard Error, cm	Standard Error, %
VP, NR, W	0.885	1.00	30
VP, NR, W, T	0.885	1.02	31
VP, NR	0.823	1.18	35
W, T, NR	0.827	1.20	36
T, VP, NR	0.824	1.21	36
W, T, VP	0.788	1.31	39
W, T	0.773	1.32	40
T, NR	0.773	1.32	40
T, VP	0.728	1.43	43
W, VP	0.720	1.45	43
W, NR	0.718	1.45	43
T	0.717	1.42	43
NR	0.631	1.58	47
VP	0.628	1.59	48
W	0.383	1.88	56

W, 24-hour wind run in kilometers; T, average 24-hour air temperature in degrees Celsius; VP, average 24-hour vapor pressure of air in millibars; R, multiple correlation coefficient. Number of observations for each analysis is 24.

Rango and Salomonson [1975] developed regression equations for April through June streamflow prediction using snow covered area extracted from satellite MSS data. A good correlation was obtained for the upper Indus River of Wyoming (see Figure 7-2). Good results using snowcovered area as the predictor for volumetric streamflow forecast also have been reported in different watersheds.

Yeh, et al. [1973] developed regression equations using a two-stage least squares estimation for prediction of volumes of seasonal runoff for Shasta and Clair Engle Reservoirs in Northern California. The two-stage least squares estimation is a technique which preserves the cross-correlation between the two drainage basins. The technique determines the regression coefficients of each equation for a system that is described by a set of simultaneous equations in which each equation contains several dependent variables that also
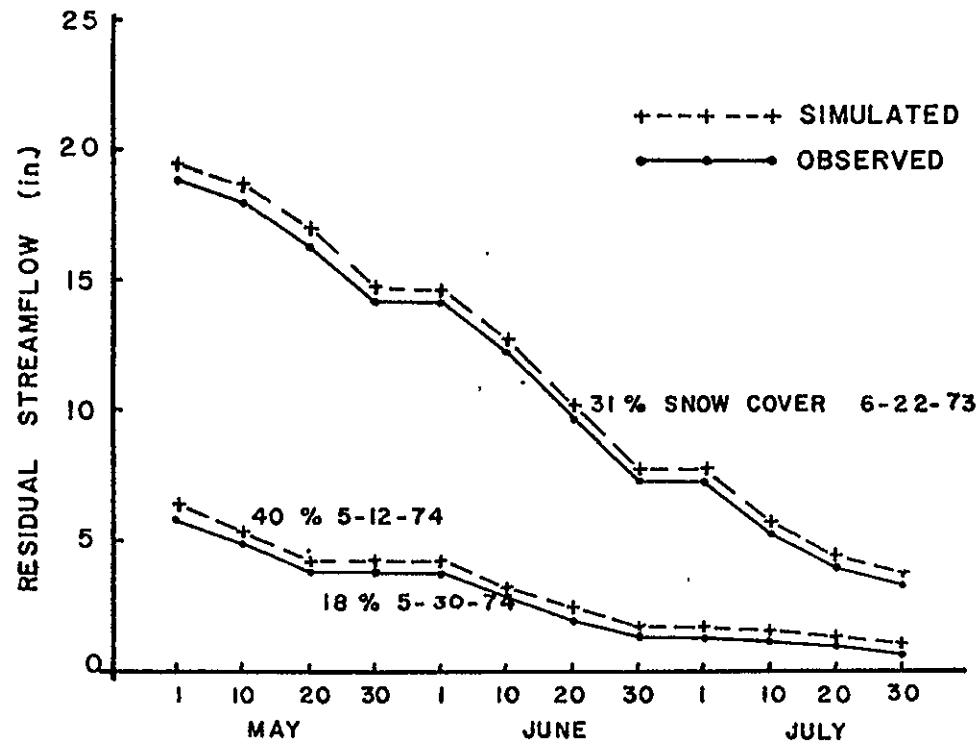
Figure 7-1. Simulated vs Observed 10-day Residual Flow Volumes for 1973 and 1974, Conejos River Basin.

(After Leaf, 1975)
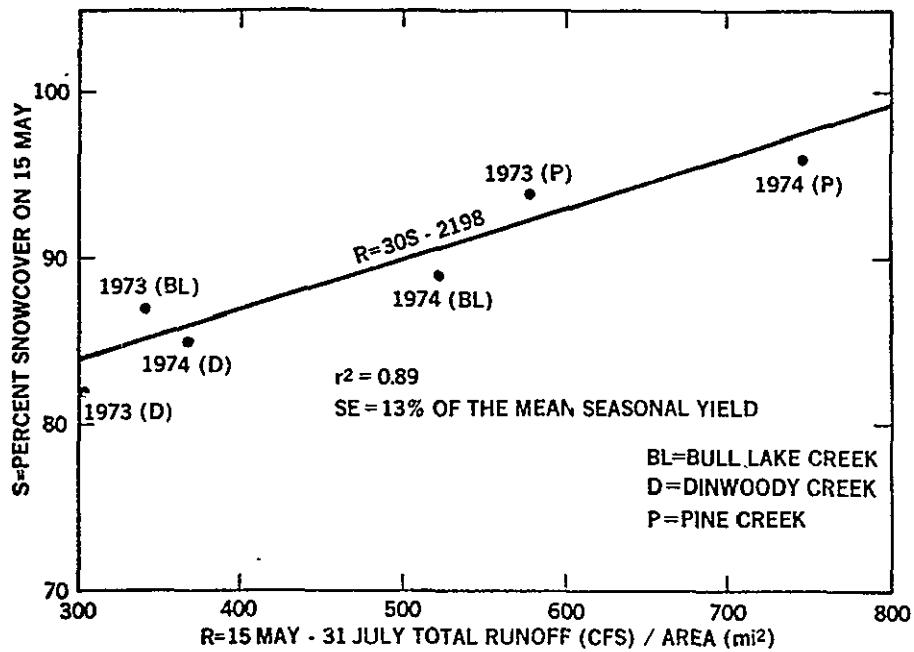
Figure 7-2. Snowcover vs Time.

occur in other equations. Independent variables used in the model include snow water content, precipitation index and previous streamflow. For 24 years of data, the correlation factor was found to be .943.

McCmillan and Smith [1975] developed regression equations for estimating point estimates of snowpack average density at certain sites based upon measurement of snow albedo (or radiance) from either aircraft-mounted or spacecraft-mounted radiometers. Several other parameters are also included as independent variables in the regression equation. The functional form of the regression equation is:

$$RHO = f(RAD, SD, DEG, I, E) ,$$

where

    RHO = average snow density (decimal)

    RAD = satellite radiance (integer)

    SD = solar declination (degrees)

    DEG = sum of average daily air temperature above freezing since snowfall (degree, F)

    I = potential solar insolation (decimal)

    E = snow course elevation (meters)

Data from eight snow courses in the southeastern portion of the American River Basin and digital radiance data from the LANDSAT MSS sensor were used to develop the regression equation. The resulting equation is:

$$RHO = 0.00125 \; DEG + 0.00243 \; SD + (2.93 \times 10^{-6})E$$
$$- (0.96 \times 10^{-6}) \; RAD + 0.339 + error \; .$$

The term I turned out to be insignificant. The multiple correlation coefficient is 0.92, with a standard error of estimate of 0.016 gm cm^{-3}, for 23 degree of freedom. However, the results show that the satellite radiance term was significant at only the 60 percent level. McMillan and Smith [1975] also developed regression equations using in situ measurements. The functional equation is

$$RHO = f(A, SD, D, R) \; ,$$

where

A = albedo (decimal)

SD = solar declination (degree)

D = days since cessation of storm (integer)

R = proportion of rain to storm in last storm (0, 0.5, 1.0) .

Using data collected in the same area McMillan and Smith developed regression equations under different cloud conditions. Results indicate that correlations are significant.

Thompson [1975] using data from LANDSAT for mapping the snow covered area, and streamflow data collected from a watershed in Wyoming developed a nonlinear regression equation for streamflow forecasting. The equation is

$$\log Y = 2.03888 + (-0.0156482)X \; ,$$

where

Y = accumulated runoff/total April 1 - July 31 runoff, and

X = snowcover/total basin area.

Using 11 data points, results indicate an excellent correlation with $R^2 = 0.98$. Figure 7-3 shows the plotted composite data and the resultant curve on a standard graphic scale.

$$R^2 = .98$$

$$\log_{10} Y = 2.03888 + (-.0156482) X$$

PLOTTED DATA

COMPOSITE SNOWCOVER
%
-V-
ACCUMULATED RUNOFF
%
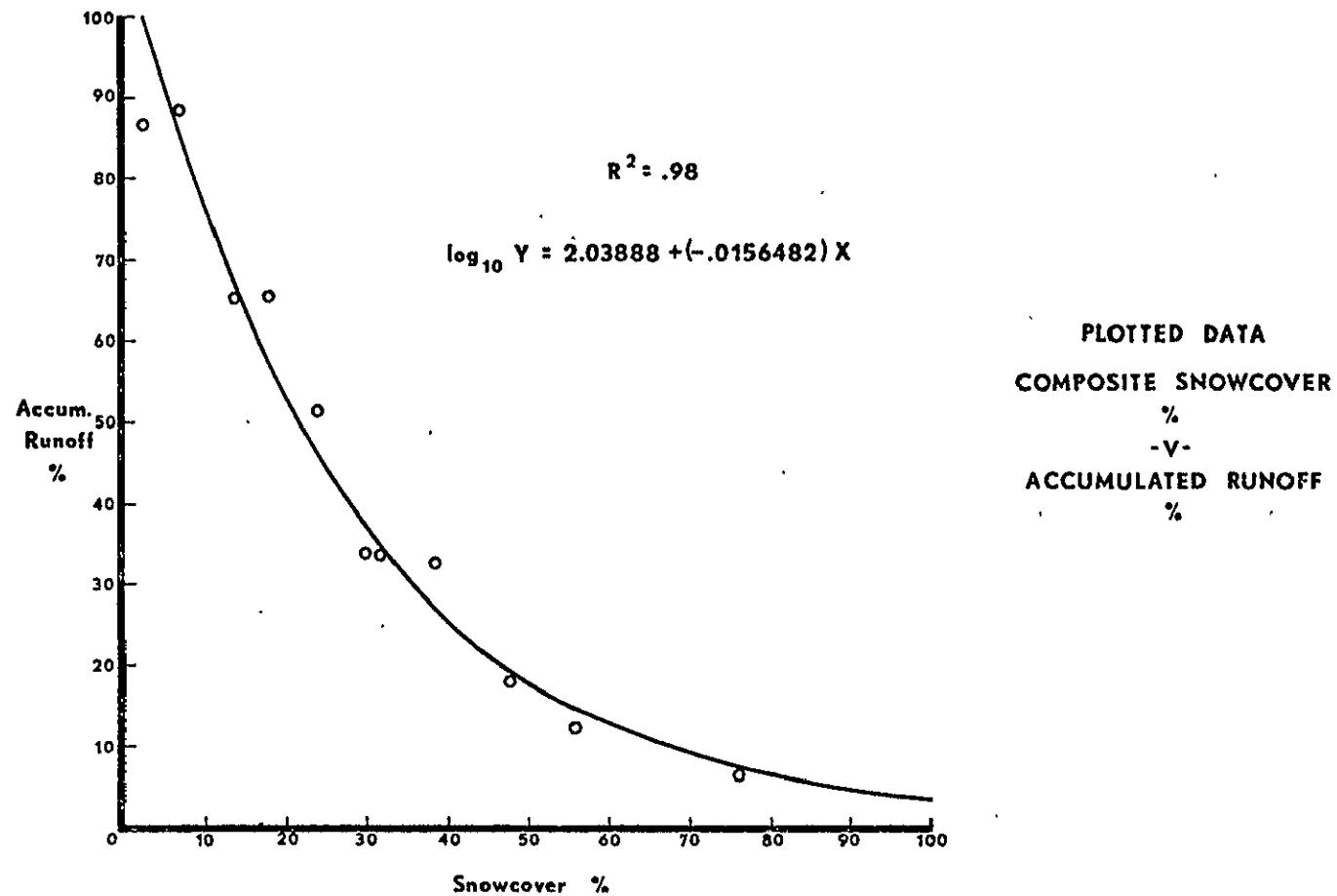
Figure 7-3. Run-Off vs Snowcover.

7.3   Snowpack Modeling

As pointed out by Smith [1970], three basic techniques have been used
in snow measurement. The first, and most extensively used, consists of one
or more of the extraction or gravimetric methods. The second, and currently
most popular, uses a weighing system (snow pillow). The third, a recent
innovation, uses isotope snow gages. The gravimetric and weighing techniques
are capable of determining the density of snow but unable to determine the
density variation as a function of depth. The profiling snow gage using a gamma
source developed by U.S. Forest Service research personnel has demonstrated
its ability to measure in situ changes in the internal snowpack structure with
changes in time. The gamma-transmission profiling snow gage as illustrated
by Smith [1970] allows us to measure the following seven factors that are
important to understanding snow hydrology:

1. Total snow depth

2. Snow density at one-third to one-half inch increments throughout
    the pack, and the average density of the entire pack.

3. Total water content of the pack.

4. Water content increase or decrease, and section of the pack in
    which the changes occur.

5. The amount of snow that has fallen since the last measurement.

6. Rainfall amount and intensity until such time as the snowpack
    begins to discharge water.

7. The melt rate between measurements.

Figure 7-4 shows the melt water moving through the pack. It can be
seen as increased density of the two later profiles over the 0840 profile (pro-
files taken by the profiling snow gage for 0840, 1325 and 1711 hrs, March 29,
1966 are plotted. As can be seen in Figure 7-4 the structure of the snowpack
has a very non-homogeneous and anisotropic structure. Snowmelt is a complex
process. The maturation of a snowpack depends upon many factors such as
soil and air temperatures, temperature within the snowpack itself, pack
density, tree coverage, and heat advected by precipitation. Phenomena such
as ice lens, wind slab, compression, effect of ice lens on compaction and
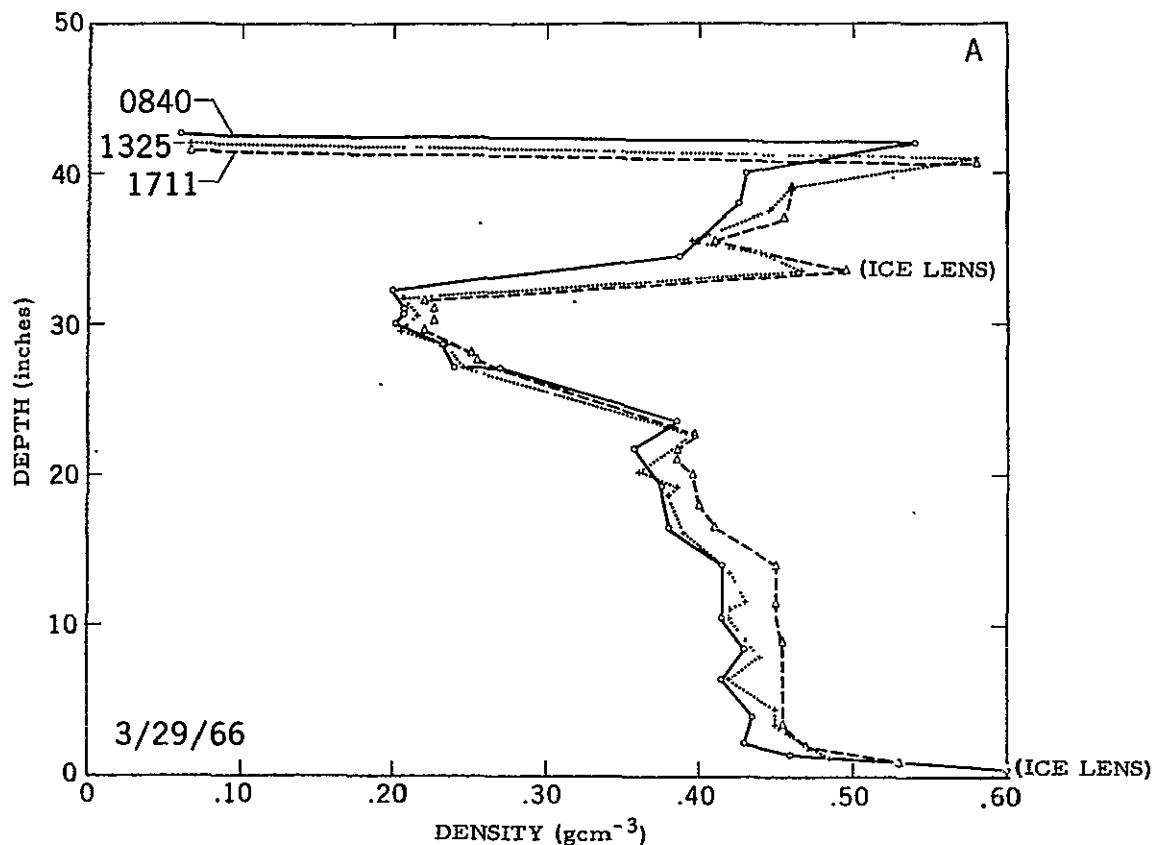
Figure 7-4. Three Profiles of the Same Snowpack Showing
Melt Occurring on March 29, 1966.
(Two ice lenses are at the surface and at 33-inch depth.)

drainage, amount of water absorbed by snowpack and pooling of water by ice
lens further complicate the snowmelt processes. These factors make mathe-
matical modeling of the snowpack prohibitively complex. In addition the rela-
tionship between snowmelt and streamflow is very complex, as illustrated in
Chapter 5.

Figure 7-5 illustrates the tremendous water holding capacity of the
snowpack as noted by Smith:

"A natural rain-on-snow event occurred from January 17 to 23, 1969.
200.66 cm snowpack containing 76.07 cm of water received 12.30 -
31.24 cm of water as snow and rain. Of the total precipitation,
17.78 cm fell as rain or as snow of 30 percent density which melted
within a few hours.
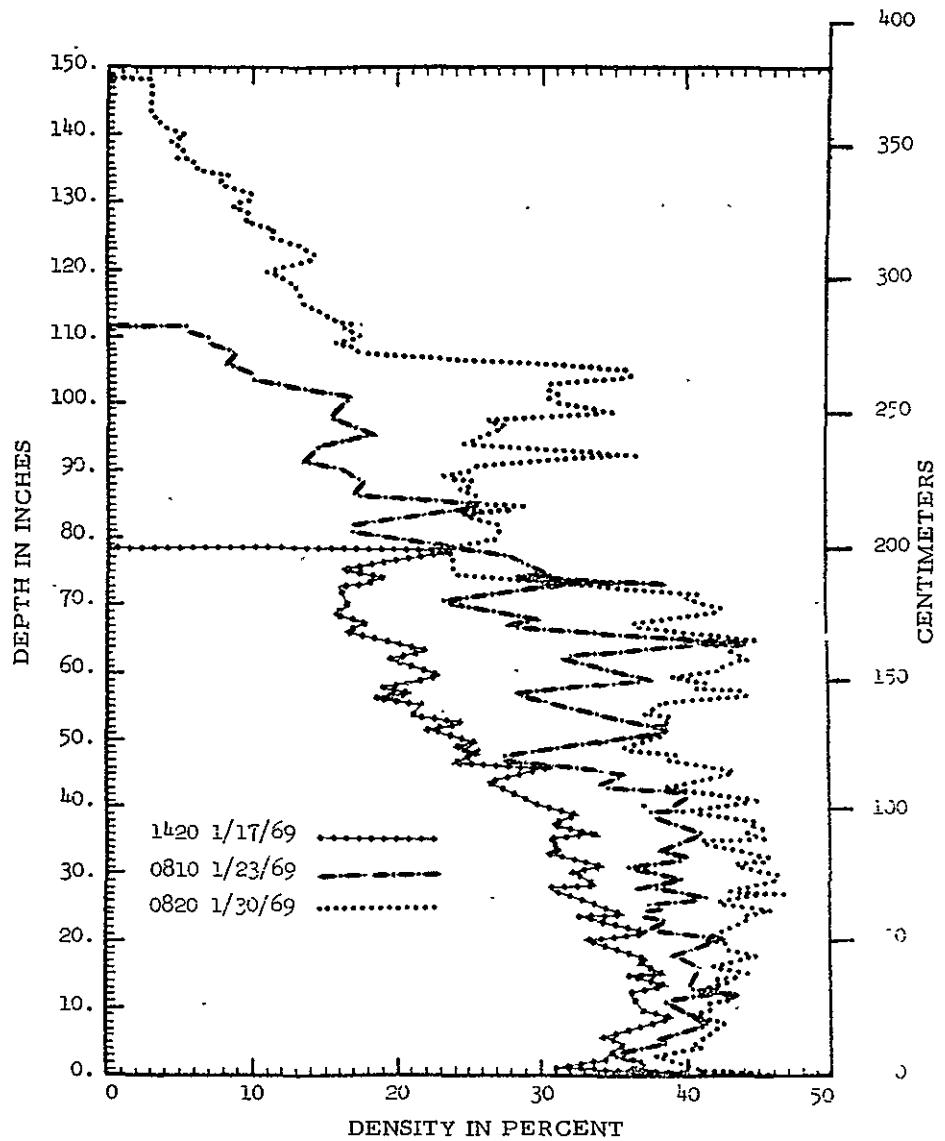
Figure 7-5. Snow Profiles of Snowpack Recorded at the
Central Sierra Snow Laboratory, California,
During a Storm on January 18-30, 1969.

(Density profile for pre and post storm,
snow pack conditions, January 17-30, 1969.)

"The original pack had a density ranging from 30 - 38 percent from ground line to 101.6 cm (Figure 7-5). Densities from 101.6 cm to 200.66 cm decreased gradually to 15 percent near the snow-air interface. The snow in this pack had accumulated from frequent storms with no intervening melt and refreezing. Thus, no ice lenses were present. Free water content as determined by freezing calorimetry was 3 percent or less. The pack had densified by compression alone. It was in an ideal condition to hold more water. After the rain stopped, new snow increased pack depth to 281.9 cm.

"The 79-inch 200.66 cm snowpack absorbed 16.36 cm of new water between January 18 - 21.. Later it absorbed another 1.42 cm of rain which fell mixed with the 68.58 cm of new snow on the 23rd. Another 2.54 cm of rain was held in the new snow. The original pack absorbed an average of 0.09 gm cm^{-3} of liquid water in the ice matrix. Liquid water increases in different snow layers ranged from 0.03 to 0.24 gm cm^{-3} over levels prevailing at the beginning of the storm."

This event points out a fundamental and serious error in many streamflow or runoff prediction models: these models assume that rainfall on the watershed immediately enters the ground hydrologic system (either draining through the snowpack or running off it). In actuality this assumption can and often does lead to large errors in inflow prediction, and in the estimation of parameter values obtained by statistical fit of observed versus predicted inflows. This shortcoming clearly needs to be addressed with further modeling research, and concomitant development of the necessary sensors.

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8. INFORMATION SYSTEMS

8.1 .Introduction

8.1.1 Background

Before proceeding with the analysis of information systems for hydropower operations, we note from the preceeding chapters that:

1. Spill mechanisms have been identified and quantified for a number of major river basins. It was concluded that spillage can be reduced or avoided only if high inflow events can be anticipated by several days (20 to 25 days of anticipation permits the hydropower operator to avoid most spills; fewer days of anticipation result in proportionately less control over losses).

2. The physical mechanisms by which precipitation over a watershed reaches the hydropower reservoir, and the hydrologic system parameters that determine the amount and characteristic lag time of reservoir inflow following precipitation (or, more generally, moisture input, which includes snowmelt), have been identified. The sensitivity of reservoir inflow volumes to snowpack and ground hydrologic parameter accuracies have been quantified; these parameters have been ranked in the order of their relative importance to inflow prediction.

3. From the knowledge of spill mechanisms, and an understanding of anticipation time in reducing spillage, the key role of weather forecasting (precipitation and snowmelt variables) becomes apparent, and its specific contribution has been quantified. Taken together, weather forecastability and the characteristic inflow lag time of the basin determine the upper bound on days of anticipation for high inflow events, and hence, an upper bound on spill reduction.

4. It is also noted from the foregoing analyses that the accuracy of streamflow prediction models is dependent upon a relatively large number of snowmelt, snowpack and ground hydrologic system variables. Improvement in the accuracy of a single variable generally

will not reduce the variance in streamflow prediction by a significant amount; improvements must be made in the measurement accuracies of several variables to be effective. Predictions of weather variables (such as air temperature, wind velocity, amount of precipitation, etc.) deteriorate rapidly in accuracy beyond 2 to 3 days; improvements in streamflow predictability through longer term, more accurate weather forecasting seem quite limited at present (the MOS weather forecast technique described in Chapter 6 offers limited but important improvements).

5. The streamflow prediction models, which are based on highly empirical ground hydrologic system and snowmelt models, are limited in their ability to simulate complex watershed runoff mechanisms in non-uniform mountainous river basins. Snow pack hydrology systems in particular are poorly represented in overall streamflow synthesis models.

The relationship between the anticipation time for high inflow events (runoff lag and weather forecastability), the accuracy of inflow prediction, and spill reduction benefits is illustrated in Figure 8-1.

These findings and observations make it possible to develop more rigorous requirements for watershed hydrometeorological information systems. Requirements as stated in Chapters 4 and 5 are compared with the capabilities of ground and air/spaceborne sensor systems as reviewed in this chapter, and sensors acceptable for application in advanced hydromet information systems are identified. A concept for such an information system is presented in Chapter 9.

8.1.2 Elements of Information Systems

Elements

An information system basically provides information to users for decision making in planning and management. The component processes in

GROUND HYDROLOGIC SYSTEM

- MEASURE SYSTEM MODEL VARIABLES
- COMPUTE I/O LAG

INFLOW TO RESERVOIR

WEATHER PREDICTION

- MEASURE SYSTEM MODEL VARIABLES
- PREDICT WEATHER VARIABLES

SNOWPACK HYDROLOGIC SYSTEM

- MEASURE SYSTEM MODEL VARIABLES
- COMPUTE MELT RATE AND YIELD RATE (WATER LEAVING PACK)

Accuracy

100%

Benefits   Prediction Trajectory

50%

Basin Lag   Weather Forecast

Days of Anticipation

WEATHER FORECAST PERIOD

DECREASING ACCURACY, INCREASING VARIANCE

BASIN DRAINAGE TIME LAG

- DETERMINABLE WITH MODERATE/GOOD ACCURACY

DAYS   OF   ANTICIPATION

Figure 8-1. Factors Affecting Inflow Anticipation Times.

such a system include data[*] collection, transmission, processing, and dissemination to the users; in principle, the system also includes the use of information derived from such data. The process of data specification is sometimes included, but is more properly an input to system development. (Its importance should not be overlooked, however; see Chapter 3.)

The sequence of processes is shown in Figure 8-2. The sensor system (or subsystem) acquires spatial and temporal data in the watershed or water
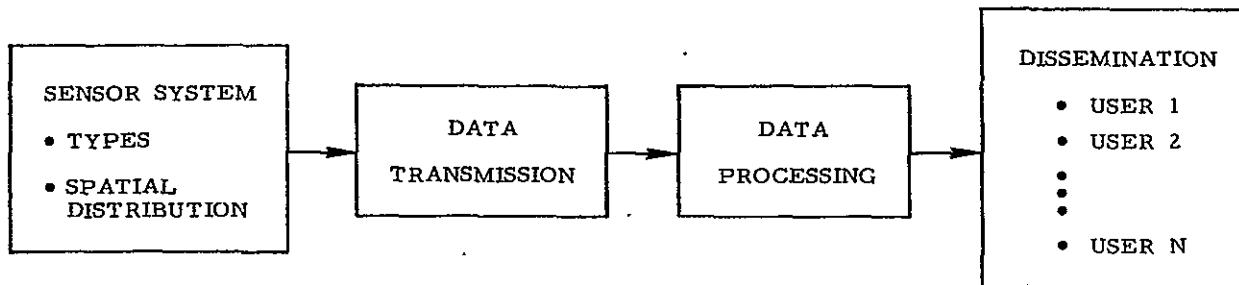
Figure 8-2. Elements of the Information System.

resource region, using both ground and air/spaceborne sensor devices. The data are usually relayed to the processing site by means of communication networks, although many present day hydromet systems contain some manually acquired data sets (e.g., snow course measurements). Computer processing is used in most major hydropower operations, although, again, manual processing of some data elements is found to be advantageous, and some degree of data interpretation is always left to the analyst or operator.

Dissemination and display of the processed data is relatively easily accomplished by communication nets of moderate capacity.

General Characteristics

It is appropriate at this point to review some of the general characteristics of the hydromet information systems that are analyzed in more detail in the following sections. Anticipating to some extent the results of the comparison of sensor requirements with candidate sensor capabilities, it is likely

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[*]Data is a more general term than information, and refers to any set of measurements whether or not taken with any purpose in mind. Data become information after retrieval and processing for a particular use.

8-4

that hydromet information systems of the late 1970s and early 1980s will rely heavily on ground sensors, augmented by LANDSAT type MSS imagery to measure snowpack spatial distribution and extent; air/spaceborne microwave sensor systems (active and passive) require much additional experimentation systems. (This eventuality would have a major impact on the types, and capacities, of data transmission and processing facilities.) The magnitude of this impact is shown in Table 8-1.

Table 8-1 presents a brief summary of the types and capacities of communication links and data processing facilities required to support the general types of sensor systems considered or proposed for advanced hydromet information system applications. Two classes of sensors are listed: ground sensors, which are of relatively conventional design except for advanced radioisotope and microwave snowpack profiler gages, and air/ spaceborne imagers, including LANDSAT MSS and microwave sensors (active and passive).

In general, the ground sensors, including the profiler gages, require communication links and processing facilities of modest capacity and cost. At the other extreme, spaceborne microwave sensors can require communication links of enormous capacities, and quite large processing complexes if data are to be processed and delivered to the user community in a timely manner, that is, one to two days after data acquisition. The LANDSAT MSS requires an intermediate level of support, but one that present communication and data processing networks do not provide.

The significant increase in hydromet information system cost that will be incurred by the introduction of high data rate microwave sensor systems is apparent; these costs may be justifiable, but a careful cost/benefits analysis. should be conducted before costly sensor system development programs are initiated.

8.1.3 Approach to Systems Analysis and Concept Definition

Figure 8-3 outlines the basic approach to the analysis of the requirements and capabilities of candidate sensors, the identification of acceptable sensors, and the development of one possible information system concept for

Table 8-1. General Data Handling System Characteristics.

Sensor System	Transmission Method	Volume of Data	Transmission Rates	Delivery Time		Cost
				To Processing Center	To User	
Ground Systems	• Hard line • Hill top • Meteor burst • Data Collection System	Very low (kilobits)	kilobits/sec	Immediate	Few hours	Low. DCS least expensive.
Air/Spaceborne Systems • Visible - IR	Dump to ground station; land lines to processing center.	High. 10s megabits	megabit/sec	Currently 1-3 weeks	Currently 3-4 weeks	Very costly. Operators cannot support without subsidy.
• Passive microwave	TDRS	High. 10s megabits	megabit/sec	Use of TDRS and costly development of processing center required to reduce time to 1-2 days.		
• Active microwave	TDRS	Extreme. 10-100s megabits	10-100s megabits/ sec			
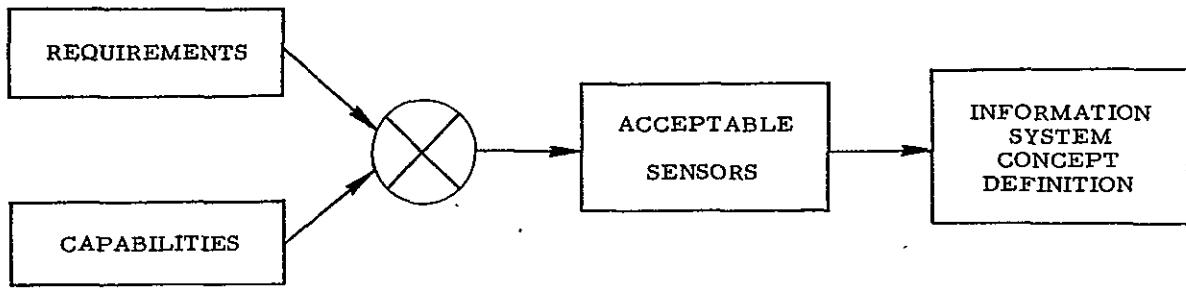
Figure 8-3. Sensor Selection Process.

application in the near term (5 to 10 years). Sections 8.2 and 8.3 present the
sensor system requirements analysis, and Section 8.4 (and Appendix D) review
sensor capabilities vis a vis the stated requirements. Chapter 9 summarizes
the system concept definition.

Sensor Requirements Analysis

Sensor requirements are based on the data input needs of the stream-
flow synthesis models presented in Chapter 4. These models include a ground
hydrologic system component, a snowmelt component, and the necessary
weather or climatic variables. Sensor requirements are quantified by perturb-
ing a representative streamflow synthesis model to determine the sensitivity of
the various model variables, including those related to snowmelt, precipitation,
etc. These variables have been ranked according to their relative importance
to inflow prediction. This important result gives a direct indication of the
improvement in inflow prediction that can be expected from an improvement
in the measurement accuracy of a given sensor or group of sensors. For
example, in Section 8.3, required sensor accuracies are stated for a set of
key high-ranked variables, such that overall inflow accuracy is maintained
within a desired limit. These results form a rational basis for assessing the
capabilities of candidate sensors, and identifying those that can satisfy an
operational requirement. It is also possible to place a bound on inflow accur-
acy, given a set of sensor capabilities. The inadequacies of the models in
properly representing the physical processes involved also become apparent.

This approach to developing sensor requirements is also highly useful
in providing guidance to sensor development programs in that it gives a
quantitative indication of the relative importance of the programs to the

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hydropower user community; alternatively, it indicates those sensors developments that will not contribute signicantly to more effective hydropower operations, even if successfully completed.

Sensor Capabilities Analysis

The review of sensor capabilities in principle is relatively straightforward; however, in actuality the relevant literature was found to be very diffuse, lacking in focus for hydropower information system applications, and replete with qualitative statements about the potentials of sensing techniques (particularly remote sensing methods) with little if any analytical or experimental quantitative substantiation. This situation has evolved partially because investigators have too easily extrapolated a potential or demonstrated capability for measuring certain parameters in a simple unform, predictable system, to highly non-uniform, complex hydrologic systems encountered in mountainous watersheds. Such extrapolations are usually unjustified. Section 8.4 is a brief but realistic summary of sensor capabilities as applied to major hydropower operations considered herein.

Information System Concept Definition

The tasks described above serve to define specifications for an improved hydromet information system, based on relatively advanced snowmelt and ground hydrologic models, improved weather forecasting techniques, and snowpack profilers that give the hydropower operator a much better indication of snowpack conditions and its likely response to forecasted weather events. Given a sensor system the supporting data collection, processing facility and dissemination system components can be defined. One possible system concept is presented in Chapter 9 based on the above approach. The concept is a preliminary one; but this approach to concept definition, if carried out in the necessary detail and supported by realistic analyses, will give a workable operational system incorporating the latest state of the art developments.

An important output of this design concept formulation process is a set of goals and objectives for advanced sensor system development programs, which in many instances today suffer from a lack of adequate and realistic assessments of potential applications.

8.2 Sensor Requirements

The major error sources in the calculation of runoff using current watershed and snowmelt models arise from deficiences in the temporal and spatial sampling of those parameters embedded in the models, from a lack of predictability of weather and other climatic factors, and from the non-inclusion of other elements which vary with time but are difficult to sense on a frequent basis. Liquid water content or density of a snowpack is an example of the latter. At the present time, developments are underway which will partly rectify the sampling problem (see Section 8.3), but these developments may take a considerable period of time. In any event, the sampling grid will always represent a tradeoff between cost and parameter measurability, variability, and relative importance in the dynamic determination of runoff.

8.2.1 Field Measurable Parameters

The parameters which are considered measurable in the field at present or with development in the reasonably near future are listed in Table 8-2. Model parameters which are not measurable but which have high runoff sensitivity rankings are listed in Table 8-3. The parameters shown are those common to most watershed models. In addition, there are several which are not contained in current models since, heretofore, they have not been easily sensed, and yet are variable with time, so that a pre-calibration procedure for these parameters is not feasible. These parameters are normally evaluated for each basin by calibration procedures.

Since anticipation of high flow events is of considerable importance, high probabilities of prediction of the weather variables, such as precipitation, temperature, wind, and insolation, are very desirable. Each additional day of high predictability would increase hydropower benefits. Some of the efforts in this direction appear promising, particularly for factors other than precipitation, but it is too early to evaluate the possible gains, if any.

8.2.2 General Requirements

It is necessary that a sensor package detect and measure those quantities relating to a high inflow event in order that the event may be anticipated

Table 8-2. Field Measurable Parameters.

Variable	Runoff Sensitivity Ranking [3]	Instrumentation	Comments	Currently Amenable to Remote Sensing	Potential for Remote Sensing
Precipitation	High	Standard rain and snow gages	Location and sampling problems	No	Storm anticipation, areal distribution possible, microwave.
Snowpack Areal Extent	High	Photo-imaging	Satellite sensing although limited by cloud cover.	Yes	
Upper Zone Tension Water	High	Electrical resistance meters	Calibration problems	No	L-band or lower frequency microwave, upper 10 cm possible.
Impervious Fraction Basin	Low	Photo-imaging	Frozen soil under snow not sensed	Sometime — see comments	
Water Surface Fraction	Low	Photo-imaging	Static parameter	Yes	
Forest Cover Fraction	Low	Photo-imaging	Static parameter	Yes	
Mean Overland Surface Length	Low	Photo-imaging	Static parameter	Yes	
Streamflow	High	Standard streamgage		No	
Insolation[1]	Low	Pyrheliometer	Field problems	No	
Air Temperature	Medium	Thermograph		No	
Humidity[1]	Low	Hygrothermograph or psychrometer	Field problems	No	
Albedo of Pack[1]	Low	Back to back pyrheliometers	Impractical for field	No	Possible correlation with active microwave reflected signals.
Wind Speed[1]	Low	Anemometer		No	
Snow Depth[2]	} Parameters not in model	Snow survey/pole markers/ radioisotope profiler	Sampling problems	No	} Depth averaged snowpack characteristics sensing by active or passive microwave requires further theoretical and sensor development and test. Good potential.
Snow Water Equivalence[2]		Snow survey/pressure pillow/radioisotope profiler	New developments	No	
Snow Liquid Water Content[2]		Microwave profiler	New development	No	
Snow Density[2]		Snow survey/radioisotope profiler	New development	No	

1. Parameter not generally used for day to day operation because of data inadequacy.
2. Parameter not generally used in current watershed models.
3. High sensitivity corresponds to absolute value ≥ 1.
   Medium sensitivity corresponds to absolute value < 1. and ≥ 0.5.
   Low sensitivity corresponds to absolute value < 0.5.
   (See Tables 5-7 to 5-9.)

Table 8-3. Non-Measurable, High Sensitivity Model Parameters.
(listed in order of sensitivity ranking)

Relative Rank	Variable
1	Lower Zone Free Water Storage Capacity
2	Lower Zone Tension Water Contents
3	Lower Zone Tension Water Storage Capacity
4	Lower Zone Primary Free Water Contents
5	Depth of Water to Fill Non-Impervious Area
6	Percolation
7	Lower Zone Supplemental Free Water Capacity
8	Upper Zone Lateral Drainage Rate
9	Percolation Shape Factor
10	Upper Zone Free Water

as early as possible. Currently available instrumentation is inadequate in this regard. (It is also remarked that streamflow synthesis models are also inadequate in that they assume that snowmelt and/or rainfall enters directly into the ground hydrologic system. In fact, several inches of rain can be retained in the snowpack with no immediate inflow to the ground system.) Some desirable sensor package characteristics for this purpose are:

1. A high confidence prediction of imminent rainstorm (or other climatic changes) within a time interval which will permit effective control action would permit a material increase in hydropower generation. The frequency of sensor coverage depends to some extent on the statistics of rainstorms over the watershed, but, in view of the limited forecasting possibilities for the near future, once a day sensing is recommended.

2. A relatively dense network of precipitation and stream gages and climatic sensors is necessary to reduce sampling error and increase the accuracy of inflow predictions. The required density is a function of the basin size, terrain, and topography.

3. Concomitant with storm prediction is the updated assessment of moisture content of the upper layers of soil (i.e., is the upper layer approaching saturation). Presently used antecedent precipitaion indices and watershed hydrologic models can be updated after the precipitation has occurred, and a hydrologic model can be used to evaluate soil moisture accurately between precipitation periods for a limited period of time. However, sensor measurements of the desired areas should be conducted at least once a week. Since there are many parameters within a hydrologic model which are difficult or impossible to measure directly, a watershed is subdivided into relatively few parts (or is treated as a single unit) and the sensor resolution requirements are not severe. A 5 km kilometer resolution for this purpose is probably satisfactory for moderately flat areas.

4. Snowpack ripeness or maturity evaluation is of the greatest importance where snowpack is a significant contributor to runoff. This would be the near equivalent of both soil moisture and rainstorm

6. Data processing on a timely basis is necessary for prompt control action. Slow turnaround of the data greatly reduces its value for hydropower operational use. Generally, this means that sensor measurements of the various model parameters should be available to the reservoir operator within no more than a day and, if possible, within hours of making the measurement. This also implies that the data should not be so complex or dense as to necessitate time consuming data reduction by the operator.

8.2.3 Quantitative Sensor Accuracy Requirements

Hydropower benefits as functions of estimation errors of various watershed parameters have been evaluated for Folsom Reservoir in Chapter 7. A single example is not a fully adequate basis for sensor specification; however, the results are considered representative.

In devising an error budget we are confronted with a tradeoff situation wherein the allotted errors can be specified in any number of ways to produce a permissible deterioration in benefits gained from a perfect sensor package (assuming no watershed model error); the degree of deterioration (or accuracy) is arbitrary. An optimal error budget would take into consideration total cost effectiveness, but the required data for this tradeoff is not available. Accordingly, the accuracy requirements for the American River watershed — Folsom Reservoir case have been calculated parametrically with the use of the snow-melt portion of the SSARR model; the results are given in Table 8-4. Two different error budgets (of many possible) have been used. For a 10% overall decrease in benefits due to parameter estimation errors, the allowable individual decrease in benefits were taken as equal and the errors were assumed independent and to RMS; for a 20% benefit decrease, the second set of 3 parameters were restricted to the benefit changes shown to limit maximum estimate errors to realistic values, and the first set treated equally. For an anticipation corresponding to the basin lag, parameter errors do not include prediction. For larger anticipation periods, parameter errors include the integrated effect of daily updated climatic forecasts.

The other parameters for which sensitivity analyses were made — the impervious fraction of the basin, evapotranspiration, air temperature above

prediction and would indicate the imminence of substantial snow-melt runoff. This evaluation would require measurements of water content or wetness of the snow, depth, and density of the snowpack, or equivalent. In the case of rain on snow, the degree of wetness of the snowpack would be a determinant of the ensuing runoff. A repeat frequency of several days during the spring melt season should be satisfactory and, as above, a resolution of about 5 km should be suitable for relatively flat areas. However, in the case of mountainous areas, where snow depth and structure can be function of elevation, resolutions of the order of 1 km or less may be necessary for sufficiently accurate estimates. Most snowpack models incorporate snowpack wetness only indirectly and empiri-cally; however, watershed models are easily modified to use fre-quently measured values of snow water content and degree of saturation.

5. Measurements of snowpack areal extent are required for a determi-nation of the quantity of melt water which may be available for run-off, depending on other factors. Most models currently employ this parameter, either as a single integrated value or for each sub-division of a watershed; the required resolution depends both on the nature of the subdivisions (if any) and the method used to process the raw sensor data. Thus, a mapping mode would require rela-tively good resolution (a few hundred meters seems adequate); an integrating sensor may require less resolution provided boundaries between areas of snow and no snow and between subdivisions of the basin representing differing snowpack characteristics can be pro-perly differentiated. Particular difficulties might be encountered late in the melt season when the snowpack might be highly patchy and irregular. Some watershed models have formulated empirical relationships between updated snowpack areal extent water equiva-lence, and residual seasonal runoff (Ref. 8-5), but these would not be adequate for the desired short term forecasting for hydropower efficiency purposes during the melt season. During the melt sea-son a repeat frequency of several days or better would be required.

Table 8-4. Allowable Parameter Estimation Errors.

Parameter	If 7 Days High Inflow Anticipation Possible[3]				If 3 Days High Inflow Anticipation Possible[3]			
	10% Benefit Decrease		20% Benefit Decrease		10% Benefit Decrease		20% Benefit Decrease	
	Prorated[1] Benefit Decrease %	Maximum Error %	Prorated[2] Benefit Decrease %	Maximum Error %	Prorated[1] Benefit Decrease %	Maximum Error %	Prorated[2] Benefit Decrease %	Maximum Error %
Precipitation (Water on Soil)	4.1	2.0	11.4	4.0	4.1	2.0	10.8	7.0
Upper Zone Soil Moisture	4.1	2.7	11.4	6.2	4.1	2.0	10.8	9.0
Snow Covered Fraction of Basin	4.1	3.4	11.4	7.8	4.1	3.0	10.8	13.0
Basin Insolation	4.1	11.0	2.0	5.0	4.1	8.0	4.0	8.0
Wind Speed	4.1	12.0	2.0	7.0	4.1	9.0	4.0	10.0
Albedo of Snow Pack	4.1	18.0	2.0	9.0	4.1	9.0	4.0	15.0

[1] Equally distributed benefit change budget, errors assumed to RMS to total benefit decrease.

[2] As above, but with second set of 3 parameters restricted to smaller budget to limit maximum errors.

[3] Reference benefit values = 27.5 GWH and 12.5 GWH, respectively.

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the snowpack, and forest cover fraction — were not allocated any part of the error budget since, in the case studied, realistic errors appeared to cause only negligible decreases in the hydropower benefits. For two of these parameters — evapotranspiration and air temperature — the initial values were such as to minimize their effects. Evapotranspiration in March was very low, as it would be during the rainy season in the American River water-shed. Similarly, the air temperature above the snowpack had an initial value near freezing. A higher initial value would have produced larger sensitivity values.

In addition, some of the parameters discussed in Section 8.2.2 are not included since they are not parameters of the watershed model used. There is probably no existing model which embodies all of these parameters since it has not been practical heretofore to quantify them. An integrated sensor package and watershed model should be developed in tandem for each to take full advantage of the other.

Thus, the results shown in Table 8-4 can only be regarded as a first preliminary try at a sensor error specification which would produce satisfactory improvements in hydropower benefits. It is emphasized that there must first be a reliable forecast of imminent (several days) high runoff. This places additional weight on the requirement for detection and assessment of storm phenomena, snow wetness, and soil moisture.

8.3   Review of Remote Sensor Capabilities

A basic problem with current ground sensors is their lack of a synoptic capability. While measurement accuracies are adequate, there can be large sampling errors, both spatial and temporal. Consequently, a major focus of remote sensor development has been to supply such a synoptic capability, alone, or in conjunction with ground equipment. Other stimuli for remote sensor utilization are higher reliability and lower costs.

A number of hydropower systems are planning to increase their ground instrumentation and to improve data transmission to the operating center. A notable example of a ground sensor network development is the Columbia River Operational Hydrometeorological System (CROHMS). However, at present there appears to be little effort to implement operational instrumentation for

a number of snowpack parameters which are important for the prediction of high inflow events — parameters such as liquid water content, pack density, and depth.

8.3.1 Remote Sensors

A major portion of the past effort towards the development and evaluation of remote (air/spaceborne) sensors suitable for hydrological purposes has been devoted to measurement of the areal extent of a snowpack. There are several reasons for this. This information is required on a more timely, cheaper, less risky, and perhaps more accurate basis to complement the customary snow survey, thus contributing towards a satisfactory estimate of the water equivalence of the snowpack and snowmelt seasonal runoff. Strategic water resource planning could then be improved by updating with frequent snowpack areal estimates during the melt season to correct to a considerable degree prediction errors in initial estimates. The technology for making such areal estimates exists in the form of visible - IR sensors, although these sensors generally cannot operate through cloud cover.

The measurement of areal extent of snowpack is, of itself, insufficient, for the purpose of improving hydropower productivity. Measurements are required that will yield better short term forecasts of runoff and streamflow, particularly high runoff events, as previously discussed. The performance of existing or soon to be available sensors is summarized from this point of view.

Visible and IR Sensors

These sensors suffer from some basic operational limitations, principally the inability to penetrate heavy cloud cover, forest cover, and fog. Also, if the satellite vehicle is at low enough altitude for good imaging, the frequency of coverage may be low, and this characteristic exacerbates the problem with cloud and fog. Partial compensation is obtained with the use of multiple satellites and more than one type of sensor. A further difficulty is encountered in the transmission and reduction of the large volume of image data and transmittal of processed data to hydropower operators. In addition, relatively low altitude satellite vehicles limit the basin size that can be observed per pass; for example, the Multispectral Scanner (MSS) on LANDSAT

will not provide complete coverage on a single pass of watersheds greater than about 34,000 sq km.

Relevant characteristics of presently used or comtemplated satellite borne visible and IR sensors are given in Table 8-5. Clearly, the emphasis of this sensor mode has been snowpack areal extent. (More or less stationary parameters such as area of forest cover are also detectable. Impervious fraction of basin has been considered detectable with visible sensors, but this is not true for frozen ground under a snowpack.) Generally, resolution and accuracy are not equivalent, and very few references to accuracy can be found in the literature. Reference 8-5 states that for the Salt-Verde Watershed (34,000 sq km) accuracies of 2 - 7% were obtained with LANDSAT MSS data, "about the same as results from low altitude aerial surveys." Thus, presently obtained snowpack areal extent accuracies are satisfactory. Frequency of coverage with LANDSAT imagery has not been satisfactory in the Pacific Northwest because of persistent overcast conditions.

The near IR band provides a capability for discriminating cloud cover from snow; however, the cloud cover limitation is not thereby removed since it still is not possible to penetrate the clouds to ascertain whether or not there is snow beneath. It has also been suggested (Barnes and Smallwood, Ref. 8-5) that melting snow can be detected by observing the reflectance of snow in the various IR bands from 0.78 µm to 1.3 µm. Meltwater on snow appears to lower reflectance. However, no quantitative data has been made available. VHRR data in the thermal IR band yielded similar results for an Alaska application (Seifert, et al., Ref. 8-5), the IR imagery being calibrated to show surface temperatures to within ±1°C. Surface weather conditions can affect the results, however.

A number of applications of satellite snowcover measurements are discussed in Reference 8-5. Snowcover vs seasonal runoff relationships are empirically derived for a number of basins with good results. However, most hydropower facilities cannot use such information beneficially for hydropower purposes since the relationships give no indication of the rates of runoff such that high inflow events can be predicted.

Leaf describes a procedure whereby periodically updated snowcover data can be inputted into a "Subalpine Water Balance Model" for the Conejos

Table 8-5. Visible and Remote Sensor Characteristics.

Sensor	Spacecraft	Altitude (Repeat Coverage)	Sensor Spectral Range μm	Parameter Sensed	Resolution at Nadir
Multispectral Scanner (MSS)	LANDSAT	920 km (18 days)	00.50 - 01.10 10.40 - 12.60	Snow areal extent	80 m - Visible and near IR 240 m - Thermal IR
S 192 MSS	Skylab	435 km	00.50 - 01.10 10.40 - 12.60 01.20 - 02.35	Snow areal extent Snow maturity	80 m - Visible and near IR
Very High Resolution Radiometer (VHRR)	NOAA	1,460 km Polar (2 days)	00.55 - 00.73 10.50 - 12.50	Snow areal extent Snow maturity	880 m - Visible
Visible - IR Spin Scan Radiometer (VISSR)	SMS/GOES	35,870 km (Stationary)	00.55 - 00.73 10.50 - 12.60	Snow areal extent	900 m - Visible 9 km - Thermal IR
VHRR	ATS-F	35,870 km (Stationary)	00.55 - 00.70 10.50 - 12.50	Snow areal extent	1.1 km - Visible
Thematic Mapper (TM)	LANDSAT (1980)	705 km (16 days)	00.52 - 00.91 01.55 - 01.75 10.40 - 12.50	Snow areal extent Snow maturity	30 m - Visible and near IR 90 m - Thermal IR

River in southern Colorado to provide short-term streamflow forecasts. The model requires energy budget data which is generally supplied by ground observations and empirical adjustments. A correlation exists in this case between snowcover depletion and residual water equivalent, and, presumably, meltwater might be deduced from the data for purposes of short-term forecasts suitable for hydropower management. However, in many cases snowmelt can occur without any change in snowcover area, particularly early in the melt season. As with the SSARR model, inflow forecasting is limited by the accuracy vs time limitations of weather forecast models, and by the accuracy in estimating the lag in the watershed hydrologic system.

Some initial studies have been made of the problems in sensing snow depth, water content, and albedo, but the available data is very sketchy. VHRR (NOAA-2) tests have indicated that snow depth can be correlated with brightness for depths to about 30 cm. However, brightness also depends on such factors as age of the top layer and temperature history of the snowpack.

Microwave Sensors

Microwave radiation at wavelengths of 3 cm and higher demonstrate good penetration of clouds, fog, and most rain. Foliage penetration is still a problem although wavelengths at L band (20-30 cm) and higher can be effective. However, longer wavelengths will result in lower resolutions unless synthetic aperture radars (SAR) are used, at the expense of considerably greater complexity and higher sensor costs. The application of these sensors to hydrological purposes is in its initial stages, and little quantitative data is available, but there have been a number of promising tests.

Passive Microwave. Snow emits thermal radiation, most of it in the thermal IR range, but a small amount of radiation can be detected at microwave wavelengths. Despite low power microwave radiation, low resolution, and complex emissivity characteristics, Reference 8-8 indicates that snow areal extent can be determined by current microwave radiometers without some of the operational problems of shorter wave radiometers. The principle used is that microwave brightness, temperatures can differentiate dry snow, wet snow, and snow-free terrain, and that snow extent can be calculated either by snow-line mapping (demonstrated by an aircraft flight over Mount Rainier with a

scanning 1.55 cm wavelength radiometer at an altitude of 10 km) or by integrating the brightness temperature values within a resolution element (requiring a number of frequency, polarization, and/or viewing angle consid- erations, depending on the number of different types of snow within the element). However, the latter method has not really been demonstrated, and thin dry packs will allow radiation from the soil, degrading the measurement accuracy. It also appears from the data of Reference 8-8 that wet snow might be difficult to distinguish from snow-free ground or from dry snow.

Finally, Reference 8-8 suggests that snow water content and water equivalence might also be determined for dry snowpack up to about 2 meters thick by judiciously varying frequency, polarization, viewing angle, etc., and noting changes in brightness temperature. These suggestions are speculative at the present time. The results of field and laboratory investigations and theoretical studies as reported in Reference 8-17 indicate that snowpack emission varies with snow water equivalent but that moist snow may present problems in separating the effects of liquid water from those associated with water equivalent. In general, the useful application of microwave radiometry will depend on a better understanding of the bulk snow properties (volume scattering phenomena) and, possibly the properties of the base soil layers. However, analytical work in this regard is under way. References 8-15 and 8-18 report similar difficulties.

The microwave radiometric investigation of snowpacks by Aerojet- General Corporation (Reference 8-17) is of particular significance in this connection, and indicates the complexities of snowpack microwave radiation and the consequent difficulties in interpreting radiometric measurements. The results of this investigation were as follows:

1. Although empirical relationships between pack water equivalence and microwave emission were demonstrated, theoretical models which approximated subsurface snow structure could provide only rough qualitative explanations of measured results but no quantitative agreement.

2. Such phenomena as ice and snow layers of varying densities and thicknesses, variable liquid water content, surface roughness, and the granular structure of the snow- and ground-pack interface

were inadequately treated by the most sophisticated current snowpack models. These phenomena require a treatment of radiation scattering and emission by random media.

3. In particular, emissions from wet snow varies with water equivalent in a complex fashion, and it was not possible to separate effects due to water equivalence from those due to liquid water. Further, soil emissions can penetrate substantial depths of snow so that information as to the nature of these emissions is important to the accuracy of snowpack measurements. Freezing and thawing of the soil and its moisture content produce significant effects.

4. On the other hand, the study indicates that it may be possible to measure the water equivalence of dry snowpacks over a broad class of terrains by radiometric means. Also, there appears to be little polarization and radiation dependent on incidence angle over the angular range of interest and the terrain slopes common in mountain snowpack regions.

Reference 8-9 reports that L-band may be used to minimize the influence of vegetation and surface roughness on soil moisture measurements by passive microwave, but that antenna size requirements (in constrast to the use of SAR for active microwave systems) would be a distinct problem. The S194 L-band radiometer on SKYLAB appeared to correlate satisfactorily antenna temperatures with a 30-day antecedent precipitation index. This would relate to the top layers of soil; longer wavelengths would be required for deeper penetration.

A Shuttle Imaging Microwave System (SIMS) has been proposed (Ref. 8-11) with radiometer wavelengths and observables as follows:

Wavelength (cm)	Observable
50, 21	Subsurface mositure
11, 4.6, 2.8, 1.7	Surface moisture
1.4, 0.81, 0.57	Precipitation and storms
0.26	Storms

A compatible IR (SCIRS) may also be used to provide additional information on surface temperature and reflectivity. Forecasting of storms with high reliability would be of great value; however, the system has yet to be proven. At the wavelengths sensitive to subsurface moisture the resolution at orbit (460 km) is 30-150 km, not adequate for use in most watershed models. (Of course, aircraft overflights are a possibility.) The corresponding resolution for sensing surface moisture is from 3-30 km which may be useful. There is no available accuracy data although aircraft radiometric measurements over bare flat fields have yielded about 5% error for moisture contents of 10%-40%.

The shorter wavelengths for surface moisture measurements must be used with caution. These wavelengths are sensitive only to very thin surface layers which can undergo wide diurnal fluctations in near-surface moisture content (Ref. 8-14).

In summary, it is difficult to reconcile the low resolution capabilities of passive microwave sensors with resolutions required to measure ground and snowpack hydrologic system parameters in mountainous watersheds with complex, non-uniform hydrologic systems. Sensors of this type are much more amenable to application to broad planar areas of uniform hydrologic makeup.

Active Microwave. Radars possess advantages over passive microwave in that they can offer very high spatial resolutions through the use of synthetic apertures, and very good temporal resolution because their power requirements do not preclude high-altitude orbits, despite the "fourth power" law. However, these advantages are compensated by high complexity and cost. Active microwave sensors suitable for measurement of dydrologic parameters are presently being developed (Refs. 8-9, 8-12).

Reference 8-13 indicates that some important physical properties of the snowpack may be obtained with multi-frequency radars (lossless and homogeneous layered media and normal incidence assumed):

1. As frequency is varied, the reflection amplitude will go through cycles of minima and maxima. Noting these values and taking measurements before and after the first appreciable snowfall,

snow and earth dielectric constants can be calculated from theoretical relationships.

2. Snow depth can be determined from the snow dielectric constant and from values of the frequency at which the first minimum is encountered.

3. The approximate average density of the dry pack can be determined by Weiner's theory of dielectric mixtures. The density distribution of the pack cannot be determined.

4. It is claimed that the wetness (liquid water content) of a wet snow-pack can be determined by the behavior of the reflection coefficient vs frequency, provided volume wetness is greater than 1%. Density may then be obtained from the relationship.

$$k = 1 + 2g + 0.21W$$

where

k = dielectric constant

g = density in gm/cc

W = percent volume wetness

5. If the reflection is specular (roughness of surface less than about 0.1λ, most of the signal return will be from the first Fresnel zone with area,

$$S = \pi H\lambda/2$$

where

H = altitude

S = area

It is estimated that the snowpack depth and density can be obtained within a ±15% tolerance, however, this has not been demonstrated even under carefully controlled laboratory conditions with simple snowpack structures. It is not clear how the technique could hope to succeed when applied to mountainous watersheds with widely variable non-uniform snowpack structures. It is not clear how well wetness can be measured in glossy media although ripening of the pack might be noted adequately by time observations of approximate wetness measurements.

Soil moisture may also be sensed by multiple polarization radar
(Ref. 8-10). Wavelengths longer than 3 cm are necessary to minimize the
effects of surface roughness. No accuracy assessments that would apply
operationally are available. Reference 8-16 indicates that difficulties may
be encountered with surface roughness effects unless long wavelengths are
used.

Reference 8-15 reports conflicting results with side looking radar
(SLAR) images of snowpack. New snow and recrystallized old snow may
not be seen.

8.4   Ground Based Sensors

The general characteristics and limitations of current ground based
sensor systems are described in this section. An important aspect of the
performance of a sensor system is the selection of sites for the sensors
which, on the one hand, adequately represent substantial areas of the water-
shed, and on the other hand, are not so located as to adversely affect sensor
operation.

8.4.1 Sensors

Precipitation. The most widely used precipitation recording gages are of
the weighing type (Friez or Stevens) which can be adapted for telemetered
data transmission. The largest source of error results from a gage catch
deficiency — an underestimate of precipitation actually falling at the gage
site. The deficiency is a function of wind, improper shielding of the gage
orifice, and the percentage of precipitation that is snow.

In mountainous terrain, as a general proposition, the orographic effect
tends to maintain the same precipitation pattern over basins which are small
relative to the area of the incident storm. Consequently, the areal distribution
of precipitation can be estimated reasonably well in many cases from point
precipitation data. Extrapolation errors depend on the specific basin and
number of stations.

Evapotranspiration. It does not appear to be practicable to sense this quan-
tity directly; it is generally estimated empirically, depending on time of year,
air temperature, and other basin climatic factors and features.

Soil Moisture. Both tensiometers and electrical resistance soil moisture meters are in common use, although the latter are preferable in that they are operable over the total moisture range. However, frequent calibration may be necesary; point to point variations may be large, and many point measurements may be required to reduce sampling errors.

Streamflow. Streamflow gages are generally the responsibility of the U.S. Geological Survey, and are maintained at stations that are so located as to enable a stage-discharge relationship to be established. Stage sensing devices can then be used to measure streamflow.

Insolation. Measurements of the radiation incident on a snow surface are made by Eppley pyrheliometers. A glass envelope excludes longwave radiation as well as some of the solar radiation, the latter because of reflection and absorption of some wavelengths by the glass. The output is a voltage, which can be telemetered in analog or digital form.

Albedo. Albedo can be measured by two back to back pyrheliometers. Albedo is determined by the nature of the surface of the snow and can change appreciably with time and location in the basin.

Air Temperature and Humidity. These may be variously measured by thermocouple and hygrothermograph. Temperature can usually be measured to within a few degrees Fahrenheit, but field problems are often encountered with humidity sensing. When in good working order, relative humidity can be measured to ±5%.

Wind Speed. Anemometers perform fairly well (generally, within 10% error). Major errors are due to icing.

Soil and Snow Temperatures. Thermocouple readings are reliable and are accurate to within one or two degrees F.

Snowpack Depth, Density and Water Equivalent. These are usually obtained manually at established snow survey sites, using the classic Mount Rose cutting tubes (or equivalent). There may be a variety of errors, depending on technique, but experienced and careful personnel can take adequate measurements. It must be noted, however, that the density values so obtained

are average densities over the depth of the pack. The area near the sampling site may be disturbed by the measurement process precluding frequent repeat measurements at the exact same site.

Depth at a relatively large number of points can be estimated using pole markers set into the ground, particularly from low-flying aircraft. However, such an operation may be too risky to undertake with any reasonable frequency.

A sensor for the measurement of pack water equivalence per unit area that has been under development and is being used in many locations in the pressure pillow. A 12-ft rubberized pillow, filled with an anti-freeze solution and suitably installed, is the minimum size that will produce adequate weighing of the snow without experiencing considerable ice bridging of the pillow. When there is no bridging water equivalence can be measured within a 10% error (Ref. 8-1).

In many watershed basins, particularly in the Sierra Nevada and the coastal ranges, density varies considerably with depth, essentially because of differential maturation of the pack. Lower layers can mature early in the season. In such cases, lower layer densities my reach 0.4 gms/cc. Also, ice or other high density layers may form over substantial areas, and melt-water or rainwater reaching this layer will flow laterally to a drainage channel without reaching the ground prior to that point (the ice layers can also cause the draining water to pool in the pack).

A profiling snowgage is being developed to obtain better estimates of meltwater runoff. Using this gage snow depth and a density profile in one-half inch increments over the depth of the pack (and thus water equivalent) can be sensed in situ and with an accuracy of about 2%. The gage is depicted in Figure 8-4 and consists of a gamma source and scintillation detector that traverse in 2 parallel vertical tubes running thru the pack and embedded in the ground. The isotope gage is considered safe and can be used at selected points for the determination of current pack structure and correlation with other areas of a basin. Figure 8-4 also indicates a density profile typical of the high degree of variability that is encountered. (See Ref. 8-21.)
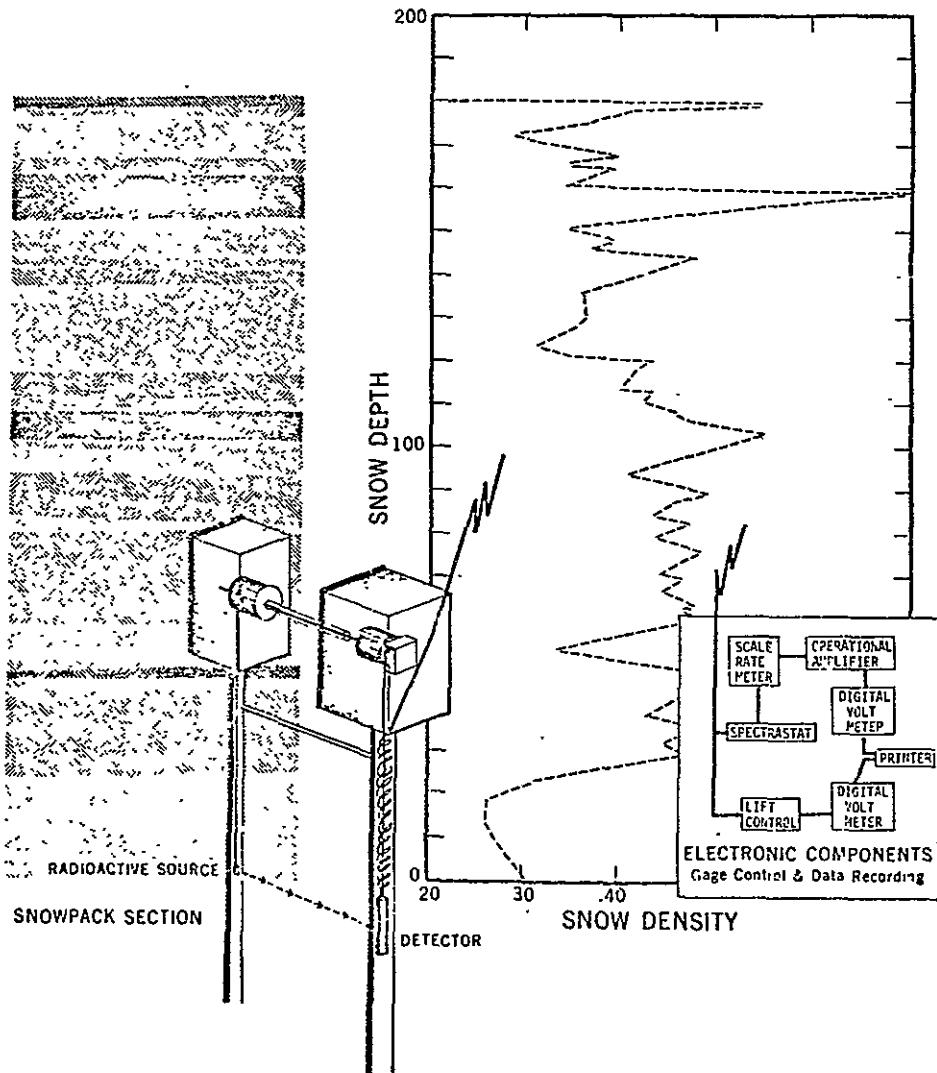
Figure 8-4. The Profiling Nuclear Snow Gage Consists
of Three Parts: 1) Source Detector, 2) Lift Unit, and
3) Signal Conditioning and Recording System.

Liquid Water Content. Calorimetric methods are very difficult to automate;
however, in a development similar to the density profiler, a microwave source
and detector moving in parallel vertical tubes has been shown to be capable of
accurately measuring liquid water content at any point in the pack. The two
profilers operating together (perhaps in the same vertical tubes) can give data
as to pack structure and condition which, when combined with climatic infor-
mation, will enable accurate short term predictions of snowmelt runoff.
(See Ref. 8-4.)

8.4.2 Columbia River Operational Hydromet Management System (CROHMS)

The CROHMS development, when completed, will constitute the most
advanced ground based runoff and streamflow informational system in the
country. The major components of CROHMS are:

1. Hydromet network which provides current hydrologic and climatic
    data by periodic automatic interrogation of the hydromet sensors.

2. Telemetry/landline data transmission to central facility and user
    terminals.

3. A central data management computer facility.

4. User Terminals which automatically receive current operational
    data with an option for user interrogation.

The hydrowet data collection stations will include continuously record-
ing sensors of precipitation, snow water equivalent, air temperature, and
wind speed and direction. A total of 437 stations are planned. Present plans
are for the entire system to be operational by 1980.

8.4.3 Data Collection Platforms

Present trends are towards a grouping of appropriate ground based
sensors on a data collection platform with hard line, ground based telemetry
or satellite data relay (such as LANDSAT or GOES) transmission modes to
a central operational station. A programming device on the platform collects
and integrates the sensor data and communicates with the central operators
in accordance with preset logic. For the foreseeable future, an optimal
operational sensor configuration will include such platforms, and ground

sensing equipment will serve both as primary data sources and as ground truth for remote sensors with greater synoptic capabilities when such sensors are developed.

8.5   Summary

To achieve improved hydropower productivity imposes a number of requirements on the sensing of pertinent watershed and runoff parameters; these are not being met by currently operational sensing systems.

The basic problems are not with ground sensor accuracies, which are sufficient, but with the lack of adequate spatial and temporal sampling and prediction of the runoff parameters, and, in fact, the virtual exclusion of the snowmelt parameters most important for estimation of daily runoff. In addition, better prediction of key weather variables would materially increase benefits to hydropower generation.

Snowmelt models which employ an energy budget for the estimation of melt water and consequent runoff involve a considerable quantity of difficult to obtain, realtime data. Thus, highly empirical approximations are often used. Tentative error budget limitations for some of these parameters are given in Section 8.3. However, it would be far more effective to deal with the problem directly: to detect and measure the water content and maturation of the snowpack. Profilers now under development have the potential for provid-ing these measurements. Measurements of snow areal extent (obtained with air/spaceborne sensors) provide additional information for an accurate esti-mate of magnitude of runoff. These measurements should be frequently updated.

There is insufficient data to judge the relative merits of remote passive and active microwave sensors for the purpose of this study. Although, in principle, microwave sensors can measure many critical hydrologic system parameters, their operational performance and capabilities are far from being proven for use in nonuniform, mountainous watershed regions; auxiliary sensor types, particularly ground sensors, would be required for calibration, ground truth, and for parameters not amenable to microwave sensing. Many water-shed model parameters, such as impervious fraction of the basin or forest cover, are amenable to measurement with satellite visible imagers, but

these parameters are slowly changing and it would not appear cost effective to burden a satellite sensor package with sensors specifically intended for this purpose. Satellite-borne sensor systems would require:

1. Parameter sensing capacities over mountainous and forested terrain, with complex ground and snowpack hydrologic systems.

2. An all weather coverage provided to a large degree by active or passive microwave. Coverage of target watersheds at least every 2 days, and, desirably, once a day is required.

3. Rapid data collection, transmission, processing and transmittal to the user community.

Satellites have an important role in advanced hydropower information systems in providing a data relay capability for remotely located ground sensors. The Corps of Engineers is currently developing networks for the relay of information from widely distributed, ground based multi-sensor data collection platforms to local and central operators in real time via satellite. In particular, the readings of widely dispersed precipitation and stream gages, as well as the output of recently developed ground instrumentation for the measurement of snow water content, could provide days of warning of imminent high reservoir inflows, which translate into considerable hydropower benefits. Ground based data platforms are particularly useful in heavily forested basins. The cost savings characteristic of this telemetry mode permit the installation of additional collection platforms to obtain better spatial resolution.

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9. AN INFORMATION SYSTEM CONCEPT

9.1 Introduction

The results and discussions of the previous sections have indicated a number of deficiencies in current watershed runoff forecasting techniques, particularly forecasts intended for hydropower operations. Major inaccuracies result from rainstorm prediction and watershed and climatic parameter sampling errors, and from a failure to consider snowpack melt, maturation, and discharge phenomena in sufficient detail and with adequate instrumentation.

A runoff information system concept is proposed in this section which will alleviate some of these deficiencies and improve hydropower day to day operations. It is clear that, for at least the 1970s, the bulk of the instrumentation must be ground based. However, since rapid data collection and dissemination is a necessity, automation and reliable hardline or telemetry (including satellite relay) of the data to a central operator are very desirable.

9.2 Data Collection Requirements

Watershed runoff and streamflow parameter sensing requirements have been discussed in Chapter 8 and are summarized in Table 9-1. The density of a sensor network that would be adequate for reduction of the sampling error to an acceptable level is very much dependent on the characteristics of the individual watershed. The values given in Table 9-1 are primarily for the Sierra Nevada, in accordance with information obtained from Dr. James L. Smith, U.S. Forest Service at Berkeley (Reference 9-1). Climatic and topographical features are sufficiently regular and uniform throughout the area to permit a relatively sparse network. Regions such as the Pacific Northwest will require parameter sensing with approximately 2-4 times the density of those given in Table 9-1. Accuracies of currently available instrumentation are considered generally adequate, although some sensors such as precipitation gages need to be sited with care and with appreciation of their limitations.

9.3 Data Collection Stations

Data Collection Platforms (DCP) have been designed to operate with LANDSAT or GOES satellites in a data relay mode to transmit

Table 9-1. Sensing Requirements.

Parameter	Measurement Frequency	Measurement Sampling Density	Comments
Precipitation	Daily	3-10 per Basin	
Soil Moisture	1 per wk	1-2 per Basin	
Relative Humidity	Daily	1 per Basin	
Wind Speed	Daily	1 per Basin	
Air Temp	Daily	1 per Basin	
Snowpack Albedo	1 per 3 days	1 per Region	A "Region" will include several Basins.
Insolation	Daily	1 per Region	
Snowpack Area	1 per wk in winter 1 per 3 days during snowmelt season	Each Basin	
Snowpack Water Equivalence	Same as Area	3-10 per Basin	
Snowpack Depth	Same as Area	3-10 per Basin	
Snowpack Density	1 per wk in winter; daily during snowmelt season	1+ per Basin	Density profile with depth required
Snowpack Liquid Water Content	Same as Density	1+ per Basin	Profile required
Snow Temp	1 per 3 days	1 per Region	Profile desirable
Soil Temp	1 per wk	1 per Region	Will detect frozen ground surface.
Streamflow	Daily	1 per Stream	

Note: Density and liquid water depth profiles probably not required for cold and dry snowpacks such as in Rocky Mountains.

hydrometeorological information to designated ground receiving stations. The LANDSAT system, for, example, is designed to relay 64 bits of data from a DCP to a receiving station whenever both are in mutual view of the satellite. In general, the reliability of the DCS has been demonstrated to be comparable or better than ground-based microwave telemetry relay systems in all cases tested. Operation of the Data Collection System requires three hardware subsystems: Data Collection Platforms, the receiving and transmitting equipment in the satellite, and special receiving and preprocessing equipment located at each of three ground receiving sites. The spacecraft acts as a simple relay: receiving, frequency translating and retransmitting the burst messages from the DCP's. No on-board recoding, processing or decoding of the data is performed. A DCS unique UHF antenna and receiver is required. Unified S-Band equipment, used for narrow band telemetry, is used to retransmit the DCP messages to the receiving sites.

Up to eight individual sensors may be connected to a single DCP. The sensors may provide digital or analog outputs to the DCP. The DCP transmits the sensor data to the satellite which in turn relays the data to the ground receiving site through an on-board receiver/transmitter. The ground receiving site equipment accepts the data and decodes and formats it for use by the hydropower system operator. Platform specifications are given in Table 9-2 and the platform is depicted in Figure 9-1. LANDSAT is at a nominal altitude of 500 miles and the orbit parameters allow for up to 9 minutes of mutual visibility for a DCP and receiving site. (GOES is stationary and is always visible.) The DCPs operate continuously, sampling the sensors periodically and transmitting a 38 millisecond burst of data containing all sensor channels at intervals of about 3 minutes.

Estimated capital cost of a CDP is $10,000 - $20,000, including possible antenna tracking equipment which would be commanded by a central facility computer. The power source, thermoelectric with propane supply, is estimated at $1,500 per platform.

The number of hydrologic and climatic sensors can be minimized through use of a hierarchy of data collection stations, and the correlation of appropriate data elements between them, in accordance with the suggestions of Dr. Smith. Table 9-3 shows the necessary sensors, stations, and costs

9-3

Table 9-2. Data Collection Platform Specifications.

ANTENNA

Electrical:

- Type   Crossed dipole with a bifolium
                                radiation pattern

- Impedance   50 ohm nominal

Mechanical:

- Reflector size   46-inch reflector disc
- Weight   21 lbs
- Mounting provision   2-inch pipe clamp at base

ELECTRONIC UNIT

Electrical:

- Signal input   8 analog channels (0-5V), or eight
                                8-bit serial digital words, or eight
                                8-bit parallel digital words, or
                                combination of the above in
                                8 word message format

- Power input   24 ± 3 Vdc
- Transmitter   FM, 5 watts output (minimum)
- Frequency   401.55 MHZ
- Power drain   56 watts for 38 milliseconds
                                (during transmissions)
                                70 milliwatts average power
                                (maximum)

Mechanical:

- Size $10.5 \times 8.5 \times 6.0$ inches
- Weight   15 lbs (maximum)
- Environment
    Temperature-operating   -40° to 125°F
    Relative humidity   0% to 97% with condensation
    Altitude   -200 ft to +17,500 ft
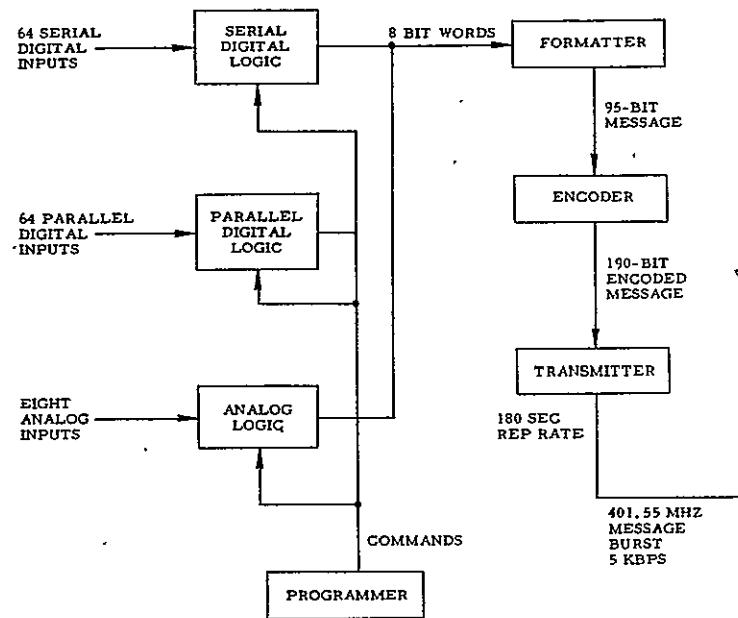
a) Block Diagram.
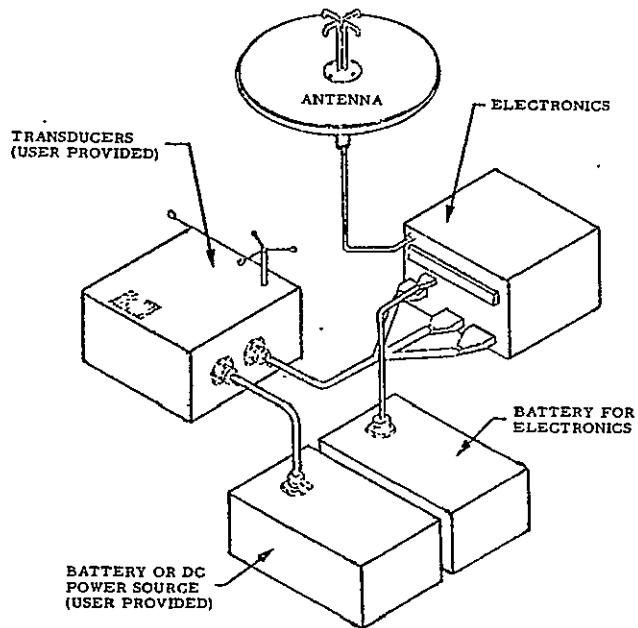
b) Equipment Components.

Figure 9-1. Data Collection Platform.

Table 9-3. Sensor and Station System Concept (Sierra Nevada).

Parameter	Sensor	Order of Station				Estimated Cost per Unit $1,000
		1st 3 per Region	2nd 1 per Basin	3rd 3-10 per Basin	4th 15-20 per Basin	
Precipitation	Heated Precip Sensor	X	X	X		1.2
Soil Moisture	Electrical Resistance	X	X			0.5
Rel. Humidity	Hygrometer	X	X			0.6
Wind Speed	Anemometer	X	X			0.7
Air Temp	Thermocouple	X	X			0.7
Albedo Insolation	Pyroheliometer — Two Req'd	X				1.2 for 2 units
Snow Area	Satellite-borne Multispectral Scanner					
Snow Water Equivalence	Pressure Pillow	X	X	X		0.7
Snow Density and Depth	Radioisotope Profiler*	X	X	(Portable)		10.0 (4.0)
Snow Liquid Water	Microwave Profiler	X	X			2.0
Insolation	Sunshine Duration		X			0.5
Snowpack Characteristics	Monthly Snow and Air Surveys				X	
Snow Temp	Thermocouple	X				0.7
Soil Temp	Thermocouple	X				0.7
Selected MOS† Predictors		X				
Streamflow	Calibrated Stage Gages	X	X	Δ		0.5

*Wilderness Act will not exclude use.

ΔGages at all tributaries.

†Weather prediction technique: Model Output Statistics (see Chapter 6).

for a wet snow region typified by the Sierra Nevada. The first order stations serve as primary reference (base monitor) stations for a geographical area with similar climatic regimes, and containing a number of watersheds. In 3 of these watersheds first and second order sites would coincide. The first order stations generally would be manned or periodically attended, and would be instrumented to gather all relevant watershed and climatic data. The second order stations collect all data required for normal operational use. First and second order data can be correlated, particularly with regard to snowpack melt phenomena to produce an accurate estimate of day to day snow-melt runoff. In turn, second and third order data correlations can reduce measurement errors arising from complex snowmelt phenomena. These phenomena are sensed by the third order station sensors, snow pillows, only in the aggregate. The manually obtained fourth order data serve as checks on the automatic instrumentation.

The total cost of data collection platform, power supply, and instrumentation (exclusive of multispectral scanner and manual surveys) for the range of stations given in Table 9-3 (and assuming 10 basins per region) is estimated to be $600,000 - $2,500,000 if DCPs are used for the third order stations. However, the top figure may be an overestimate since cheaper platforms or the use of one platform to serve several third order stations with ground to ground data transmittal between them might be preferable.

With regard to the Wilderness Act, efforts are currently underway (Sisk bill) to legitimatize reasonable data collection. In any event, at present sensors such as the density profiler may be used at existing snow survey sites and correlations made with other stations.

9.4   Central Operational Facility

Operating agencies such as the Corps of Engineers and Bonneville Power Administration for the Columbia River drainage and the Bureau of Reclamation for the Central Valley Project of California are planning and designing central operational facilities to expedite and assist the system operators in the management of their water resource systems. Such a facility is essential for a successful and timely integration, analysis, and utilization of the collected hydrometeorological data for streamflow forecasting and

hydropower optimization. The nucleus of the facility is a data management computer system capable of interrogation access to all data collection stations. The facility will store historical data and provide retrieval capabilities for such data as a backup in the event of failure of some of the collection stations or transmission facilities, and for statistical analyses purposes. A portion of the computer will be reserved for calculation of optimal reservoir release policies in accordance with updated watershed runoff forecasts. A command and control section will exercise centralized regulation of the DCPs and will interact with allied service computers as necessary.

In addition, the computer can be used to apply the Model Output Statistics (MOS) program, as described in Chapter 6, to predict weather and other climatic factors on the basis of local observations of prediction variables made at various stations. These observations can be relayed through a DCP, or can be communicated by hardline.

9.5 Data Communications System

The preferred mode of data transmittal to the central facility is by satellite relay, although a detailed trade-off with conventional ground relay techniques is required to justify the use of satellite relay for specific watersheds. The reliability of this mode has been demonstrated by LANDSAT to be comparable or better than ground based microwave relay systems. Furthermore, there can be significant cost savings; it has been estimated that a $3 million telemetry cost for the Pacific Northwest HYDROMET installation in the Willamette Valley could be reduced to $1 million by using the GOES data relay system.

The New England Division, Corps of Engineers (NED) has had 3 years of experience with its 26 station network using LANDSAT data collection, and espouses the concept of local user terminal (LUT) type ground receiving stations for the smaller regions. The station is relatively inexpensive, semi-automatic and easily maintained. Figure 9-2 is a block diagram of the station. The software to drive the antenna system is being developed to operate the antenna automatically at nighttime and weekends with a minicomputer controlling all functions.
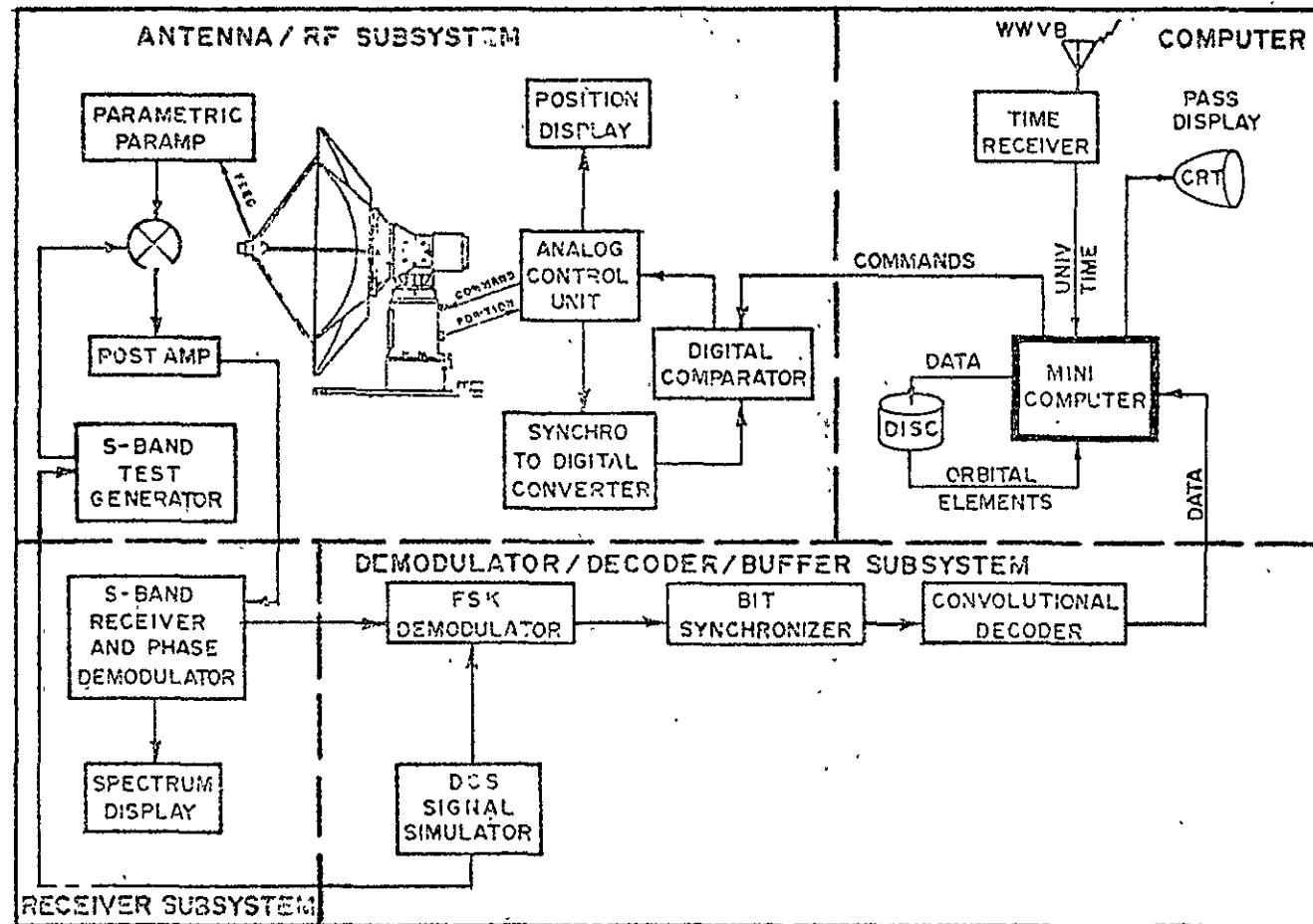
Figure 9-2. Subsystems, Devices and Information Flow
in LANDSAT Local User Terminal.

The mini computer is a very active component of the LUT. It periodicaly interrogates a radio station for the correct Universal Time, controls the 15-foot diameter antenna and acquires data virtually simultaneously by multitasking programs. By accurately knowing the time of day and the satellite's precise predicted position, the computer easily keeps the satellite within the antenna's three degree receiving beam width. Current plans call for the total slave mode of operation, i.e., tracking depends on the computer being informed correctly. However, there are being developed software autotracking packages which will be more versatile. With these, if for some reason the satellite were outside the antenna's receiving beam, the computer would execute a search for it and order changes in antenna direction and movement to bring it back into view.

A similar system is scheduled to be operational this year by the Lower Mississippi Valley Division of the Corps of Engineers. Cost estimates for LUT equipment and installation are $168,000, including development test and operations.

Sensor data is of sufficient importance to warrant backup transmittal systems, at least from the second order stations. The choice depends on the situation and may be dedicted hardline, multi-channel carrier equipment coupled to transmission lines, or other means.

Multispectral scanner data must be transmitted at a comparatively high bit rate and direct transmittal to a user station is probably not practical. However, current time lags are not desirable and a speeding up of the procedure to put snowpack areal extent information into the hands of the users within one day of the observation is a requirement for optimal utilization of the information during the melt season.

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10. CONCLUSIONS

The following conclusions are drawn from this study.

1.   Energy Loss Mechanisms

The major energy loss mechanism is the spillage of water — a forced release of water when the power pool is full and inflows are greater than turbine capacity.

A major cause of spillage is the inability to predict short term, high inflow events with sufficient accuracy, such that storage space can be made available in anticipation of the event. If high inflow events can be predicted, spill reduction and the consequent benefits increase in a roughly linear fashion with anticipation time and with forecast accuracy (up to three to four weeks).

Benefit functions have been derived for Folsom, Shasta and Trinity Reservoirs of the Central Valley Project; for the main stem of the Columbia River and the lower Snake River; and for the large hydropower plants in the upper Missouri River Basin. Improved short term streamflow predictions can produce benefits of about one-half percent to one percent of annual generation for each day of high inflow anticipation. Three days of anticipation at Folsom with 80 percent accuracy will yield an additional 10.5 GWH of energy per year, an equivalent benefit of $52,500 at $5,000 per GWH. A rough extrapolation to all of Northern California (based on analyses of Shasta, Trinity, Folsom and Oroville) gives an annual benefit of 200 - 300 GWH.

Additional large benefits are possible if inflow forecasts are sufficiently accurate to permit reductions in the size of flood control reservations; this could be done for high confidence forcasts only. For Folsom an increase of approximately two percent of annual energy generation can be achieved per day of anticipation.

A second major cause of spillage is due to under-estimates of seasonal run-off, such that less than allowable releases are made early in the season. This type of loss mechanism can occur with very large reservoirs (power pool approximately equal to total seasonal run-off). The large reservoirs on the Missouri are in this category, but analyses indicate little likelihood of beneficially altering the release schedules of these reservoirs because of downstream flow constraints.

Better seasonal estimates can also serve to reduce flood reservations when these are determined (in part) by expected run-off for the remainder of the season.

2.   Role of Improved Information Systems

Hydropower output can be increased through use of information systems that provide increased anticipation times and accuracies for high inflow events. There are two basic anticipation mechanisms. The first is weather and climatic forecasting; current forecast methods limit the anticipation time for reasonably accurate forecasts to less than three days.

The second mechanism is hydrologic system lag time, i. e., the time between rainfall or snowmelt and inflow to the reservoir; this lag time is a function of the system topography and geometry, the value of the snowpack and ground hydrologic system state variables, and the locations of the reservoirs with respect to the watersheds. This lag is normally in the range of 0 - 5 days.

3.   Hydrologic System Modeling

A hydrologic model is required for the short term inflow forecasting process. The accuracies of existing models are reduced because they do not represent the snowpack as a complex, time-varying hydrologic system which interfaces with a ground hydrologic system. Snowpack parameters such as density and liquid water content profiles, which determine drainage rates during the all-important melt season, are not utilized. In addition, although the better models include options for sub-basin partitioning and snowpack energy budget calculations, these options are rarely used for lack of sufficient data.

Current hydrologic models employ a relatively large number of parameters; the most sensitive of these simulate underground soil physics and are not amenable to sensing in the field. Those variables which are available for sensing and have high sensitivity values (ratio of percent change in run-off to percent change in variable) are, in approximate order of importance:

1)   Precipitation amount

2)   Upper Zone Soil Moisture content

3) Snowpack area, Water Equivalence

4) Insolation, Air Temperature, Wind Speed.

Most models do not obtain the data for item 4). Water equivalence of the snowpack is currently sampled by pressure pillows (and manual surveys) and is sometimes used in estimating total seasonal runoff. Other aspects of the snowpack structure which are vital to daily inflow forecasts and to time lag estimates between precipitation and inflow can be sensed with radio isotope/microwave profilers, but these are not in operational use. Snow depth, density profile and liquid water content profile, which are strong indicators of pack maturity, can be sensed with these devices. These snowpack parameters rank in importance between items 1) and 2) during the snowmelt season.

Because many variables contribute to the overall accuracy (variance) of the model, a large improvement in any one variable will not reduce total variance appreciably.

Short term streamflow predictions on the basis of hydromet modeling of watershed runoff phenomena are used only by a few major hydropower operators, but the use of such models is gradually being extended. Programs should be initiated to encourage and support the extension of information systems using this technology to a broader sector of the hydropower industry.

4. Synoptic Models

A number of investigators have developed relationships between fraction of total seasonal runoff and the fraction of basin area covered by the snowpack, based primarily on LANDSAT MSS data. Good correlations have been obtained for selected watersheds for one or two snow seasons. If a high degree of correlation can be obtained over a number of years of observations, the relationships would help improve refill strategies for reservoirs, particularly those that derive a major fraction of season inflow from the snowpack. Data gathering for this purpose has been impaired by lack of cloud-free viewing time over major watersheds in the Pacific Northwest, which is the major producer of hydropower in the United States.

5. Weather Forecasting

Weather forecasting shows rapidly decreasing accuracy with time and quantity of precipitation; accuracy levels seldom exceed 30 percent, and

predictions generally are limited to 2 - 3 days. Since high inflow events must be forecast with reasonable accuracy for improved hydropower benefits, both of these characteristics reduce its effectiveness. Use of historical records for local weather patterns (the "MOS" technique) can yield improvements, both with regard to precipitation probability and amount, and to factors such as wind and air temperature. The MOS technique is presently being tested for use in the Columbia River-Basin. The use of remote sensors for enhancing weather predictions for hydropower uses does not appear promising for the near term.

6.   Remote Sensors

The only significant and proven remote application of air/spaceborne sensors to date is the use of visible and IR photoimaging for the sensing of snowpack area. These sensors are operationally limited by cloud and forest cover and by the requirement for sufficiently low altitude for good imaging. The latter results in low frequency satellite coverage, which exacerbates the cloud problem. Nevertheless, MSS sensors are useful for updating snowpack areal extent when such sensing is feasible.

The extent of forest cover and other hydrologic model parameters can be sensed by these sensors but there is little cost incentive for such sensing because most such parameters are relatively unchanging. IR sensors can detect meltwater on snow, but such meltwater is a diurnal occurence and no particular indicator of snowpack maturity.

Remote microwave sensors are in the initial stages of some promising developments, but considerable theoretical and developmental efforts are required to make these sensors operationally useful. Both passive and active sensors can be potentially effective in the frequency bands less than 10 GHZ, although dense foilage will always present problems; passive microwave at orbital altitudes suffers from poor resolution and low signal power.

Basic difficulties for both types of microwave sensing arise from the complex nature of the snowpack and its interface with the ground hydrologic system, and the extreme non-uniform conditions over the watershed. It may be possible to develop simple, inexpensive reflectors placed at various heights above the ground, and distributed at key watershed locations, to enhance the effectiveness of active air/spaceborne microwave "probes."

With a few exceptions, there is a lack of quantitative data, either from analytical or experimental studies, to perform a detailed assessment of the feasibility of measuring hydrometeorologic model variables with air/spaceborne microwave sensors.

7.   Information System Concept for the Near Term (to 1985)

Based on a review of sensor requirements and state of the art and near term capabilities, it appears that improvements in information systems for hydropower operations will depend primarily on more extensive use of ground based sensors in conjunction with better ground and snowpack hydrologic models, MOS weather forecast techniques, and satellite data collection systems. The Columbia River Operation Hydromet Management System (CROHMS) incorporates many of these elements, or is planning to do so. The basic hydrologic model of the SSARR type contains the requisite snowmelt and split watershed options. A denser sensor net and correlation of field data with that obtained from heavily instrumented reference stations in the area would support such options and would reduce sampling errors, which are a major error source for these models. In addition, recent ground sensor developments, such as the microwave liquid water profiler and the radio-isotope density gage, make possible a much more adequate treatment of snowpack structure and maturity than heretofore. MSS supplied snowpack areal extent information is desirable, updated as frequently as is feasible. MOS weather forecast techniques would tend to increase high inflow anticipation.

11. RECOMMENDATIONS

In addition to on-going activities discussed above, the following recommendations are made for new analyses and R&D program activities.

1) Reformulate watershed runoff models to include snowpack parameters such as density and water content profiles and water equivalence. Adequately subdivide a heterogeneous watershed into subregions.

2) Initiate demonstration tests of selected air/spaceborne microwave sensors for measuring snowpack state conditions including passive "reflector" aids.

3) Develop reliable, low cost ground based sensors for measurement of precipitation and soil moisture.

4) Expand the use of satellite data relay systems techniques for selected projects and for specific regions.

5) Determine the effectiveness of MOS outputs for snowmelt prediction.

6) Establish through analyses the inflow forecast reliability necessary for the hydropower operator to use such forecasts regularly in his determination of reservoir release policy.

7) Determine acceptable forecast reliabilities for reducing reservoir flood control space in response to these forecasts.

8) Initiate a nationwide program for the use of advanced hydromet information systems for control of relatively short term high inflow events. Specifically:

   a. Extend survey of hydropower installations to determine types of hydromet information systems required, and the number of installations requiring each type; the analysis methodology outlined on page 2 is well suited for this purpose.

b. Initiate and support a program to disseminate the modeling, instrumentation, and computer-communications system technology to the user community defined in (a).

c. Encourage and support the development of efficient, inexpensive instrumentation to monitor snowpack conditions.

d. Encourage and support the development of more effective hydromet modeling technique for the user community identified in (a). These are the prime elements in predicting dynamic inflow events.

e. Prepare and disseminate to the user community planning implementation guidelines manuals for hydromet information systems including data acquisition, transmission and processing.

APPENDIX A

ADDITIONAL WATERSHED MODELS

AND SENSITIVITY CURVES

APPENDIX A.1

ADDITIONAL WATERSHED MODELS

In addition to GSSS and SSARR models reviewed in Chapter 4, several other models are reviewed and summarized in the following sections.

1. The Stanford Watershed Model IV

The Stanford Watershed Model developed by Crawford and Linsley [1966] is the pioneering effort in modeling the runoff cycle from precipitation to streamflow by dividing the overall watershed response into individual components, each representing a known hydrologic process described by an empirical expression. The Stanford Model has been changed frequently since research on digital models of the hydrologic cycle began in 1959; Crawford and Linsley have designated five versions of their model by number. Crawford has continued updating the model in his work at Hydrocomp International [1969]. The original version of the Stanford Watershed Model was written in the Burroughs computer landguage (BALGOL) used by the Stanford Computer Center. James translated into FORTRAN IV the Stanford Watershed Model III as reported by Anderson and Crawford [1964]. Later, a number of improvements of Model IV [1966] were added along with other adaptations suited to the climate and geography of Kentucky, which is representative of the humid eastern portion of the United States.

Figure A.1-1 is a flow chart showing structure of the Stanford Watershed Model IV. The input parameters include rainfall and potential evapotranspiration in addition to physical descriptions of the watershed and its hydraulic properties. A complete description of the model is not given here since characteristics of the model are basically the same as that of the Kentucky Watershed Model, which will be detailed later.

1.2 The Kentucky Watershed Model

The Kentucky Watershed Model [James, 1970, Liou, 1970, and Ross, 1970] is a FORTRAN translation of the Stanford Watershed Model originally developed by Crawford and Linsley [1966]. In addition, routines (OPSET)
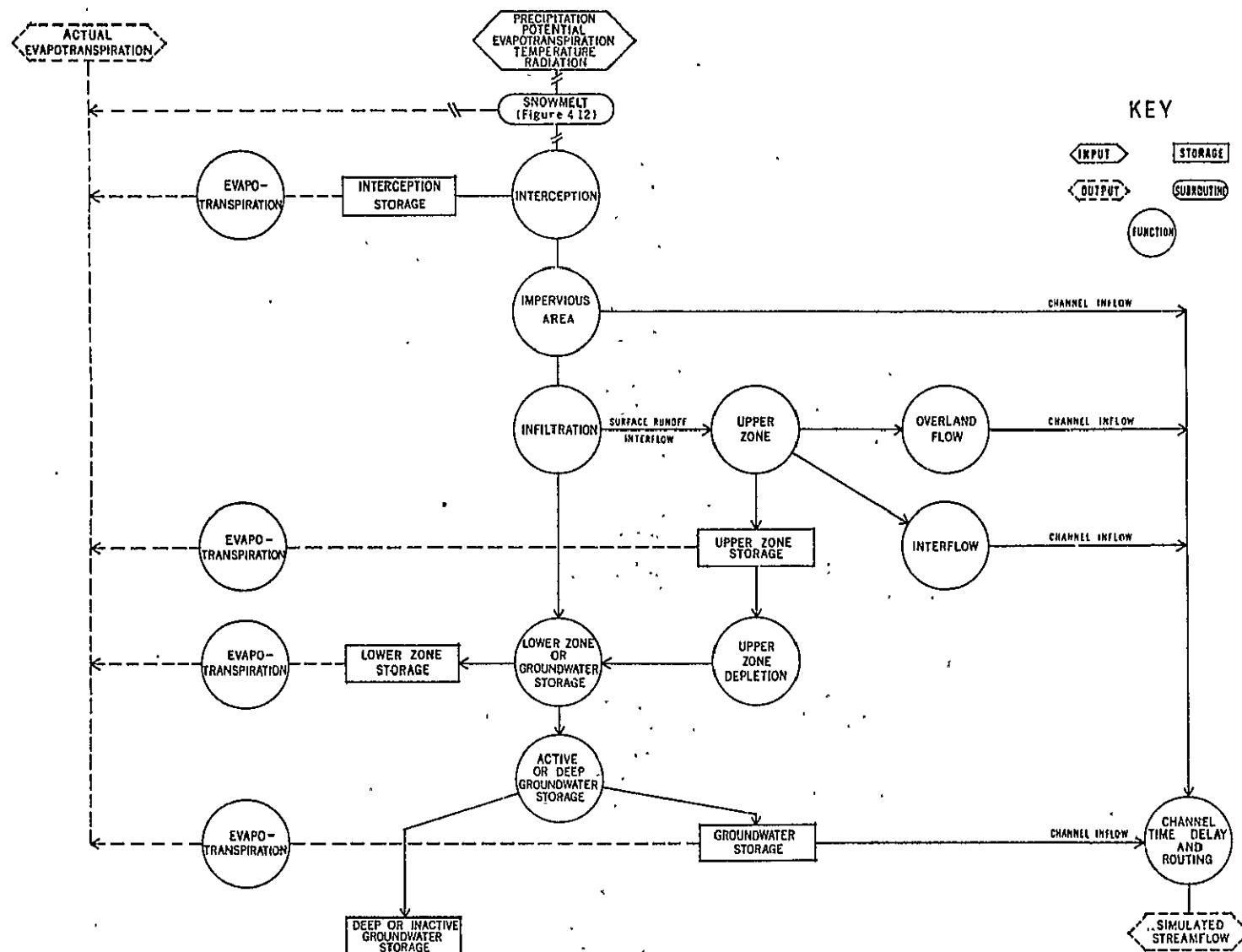
Figure A. 1-1. Stanford Watershed Model IV Flowchart.

have been added for automatic optimization of parameters by successive iteration.

The characteristics of the Kentucky Watershed Model are:

INPUT DATA

1. Control Data to specify the desired program options and request specific output.

2. Starting Moisture Storage Values as of October 1

    - Current groundwater storage.
    - Current upper zone storage.
    - Current lower zone storage.
    - Current value of base flow nonlinear recession index.
    - Interflow storage.

3. Climatological Data

    1) Rainfall Data

        - Hourly rainfall totals from recording gage.
        - Auxiliary rain gage daily totals.

    2) Evaporation Data

        - (Option 1) — Daily lake evaporation data and monthly evaporation pan coefficient data.

        - (Option 2) — 10-day average lake evaporation data and the monthly evaporation pan coefficient data.

        - (Option 3) — Estimated potential annual evaporation with mean annual number of rainy days.

4. Snowmelt Data (optional)

    - FIRR   — Fraction of incoming radiation reflected by snow surface as a function of age.

    - RICY   — Radiation incidence over the calendar year.

    - DPSE   — Daily potential snow evaporation.

    - BDDFSM — Basic degree day factor for snowmelt.

4. Snowmelt Data (optional) (contd)

- SPBFLW — Snow pack basic maximum fraction in liquid water (i.e., maximum storage of liquid water that can be contained in the snowpack).

- SPTWCC — Snowpack minimum total water for complete basin coverage.

- SPM — Snow precipitation multiplier (i.e., snow correction factor).

- ELDIF — Elevation difference between base temperature station and basin mean elevation.

- XDNFS — Index density of new snow (i.e., snow density) at or below 0°F to calculate the density of new snow (DNFS) for temperature above 0°F as $DNFS = XDNFS + (T/100)^2$ where T is a temperature.

- FFOR — Fraction of the watershed being forest.

- FFSI — Fraction of snow on forest intercepted.

- MRNSM — Maximum rate of negative snowmelt (snow chilling).

- DSMGH — Rate of daily snowmelt from ground heat.

- PXCSA — Precipitation index for changing snow albedo.

- SIAC — Seasonal infiltration adjustment multiplier by which the infiltration rate increases in the wet season.

- ETLF — Evapotranspiration loss factor to estimate the volume of evapotranspiration from the lower zone.

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5. Watershed Parameter

1) Parameters recommended for determination directly from observed watershed characteristics.

- AREA — Area of the watershed in square miles.

- FIMP — Fraction of the watershed covered by impervious area.

- FWTR — Fraction of the watershed covered by water surfaces.

- VINTMR — Vegetative interception maximum rate.

- GWETH — Groundwater evapotranspiration factor.

- SUBWF — Subsurface water flow out of the basin.

- OFSS — Average slope of the overland flow surface.

- OFSL — Average overland flow surface length.

- OFMN — Manning's roughness coefficient for overland flow on soil surfaces.

- OFMNIS — Manning's roughness coefficient for overland flow over impervious surfaces.

- DIV — Mean daily flow diversion into the basin.

- CHCAP* — An index channel capacity providing an estimate of the flow at the mouth of the watershed which is associated with the beginning of widespread flooding from tributary channels.

2) Parameters recommended for estimation by OPSET (an optimizattion routine) through comparison of synthesized and recorded streamflow statistics.

Recession Constants

- IFRC — Interflow recession constant.

- BFRC — Base flow recession constant.

---

*CHCAP can also be adjusted by OPSET.

5. Watershed Parameter (contd)

   2) (contd)

   Land Phase Parameters

   Runoff Volume Parameters

   - LZC — Lower zone storage capacity which approximately equals the volume capacity of the soil to hold water.

   - BUZC — Basic upper zone storage capacity to store water in interception and depression.

   - SUZC — Seasonal upper zone storage capacity factor.

   - BMIR — Basic maximum infiltration rate to control the rate of infiltration.

   - SIAC — Seasonal infiltration adjustment constant.

   - ETLF — Evapotranspiration loss factor to estimate the potential evapotranspiration rate.

   Interflow Volume Parameter

   - BIVF — Basic interflow volume factor controlling the time distribution and quantities of moisture entering interflow.

   Channel Routing Parameters

   - CSRX — A streamflow routing parameter used to account for channel storage when channel flows are less than one-half capacity (CHCAP).

   - FSRX — A streamflow routing parameter used to account for channel plus flood-plain storage when streamflows are greater than twice the channel capacity.

Note: When the time-area histogram is used with OPSET, the histogram elements are automatically adjusted to achieve the best match of the simulated with the recorded hydrographs.

STREAMFLOW ROUTING INTERVAL: 15 minute or hourly.

PROCESS SIMULATED:

1. <u>Interception</u>: An initial abstraction from precipitation limited to a present maximum. Intercepted water removed by evaporation at the potential rate.

2. <u>Impervious area</u>: A present percentage of precipitation diverted directly to runoff representing rainfall on streams and directly connected ponds, lakes and impervious area.

3. <u>Infiltration</u>: A variable function of soil moisture.

4. <u>Partial area runoff</u>: Infiltration capacity assumed to vary linearly over watershed.

5. <u>Overland flow</u>: Equation based on turbulent flow and fitted to experimental data.

6. <u>Surface retention</u>: Upper zone storage filled at a rate which decreases as quantity in storage increases and is depleted by evapotranspiration at the potential rate.

7. <u>Soil moisture</u>: Lower zone storage filled by infiltration and percolation from upper zone. Depleted by evapotranspiration at a rate dependent on water in storage.

8. <u>Groundwater</u>: Replenished by percolation from lower zone at a rate varying with lower zone storage. Depleted by contribution to streamflow as a variable function of amount of groundwater storage. Evapotranspiration from groundwater and percolation to deep aquifers can be simulated.

9. <u>Interflow</u>: A portion of the infiltration diverted to interflow, the fraction increasing as lower zone storage is filled.

10. <u>Channel routing</u>: Flows delayed by time-area histogram and routed through a linear reservoir at outlet.

11. <u>Snowmelt</u>: Contains functions which discriminate between rainfall and snowfall, control accumulation of snowpack water equivalent and density, and calculate rate of melt.

1.3   National Weather Service River Forecast System (NWSRFS)

The hydrologic forecasting service of the National Weather Service [1972] has tested three watershed models. These were:

1.   The SSARR Model,

2.   The Sacramento River Forecast Center Hydrologic Model (GSSS), and

3.   The modified Stanford Watershed Model IV.

The models were tested on six river basins representing various climatic and hydrologic regimes of the contiguous United States. It was concluded that there is no overall statistical difference in the accuracy of model output between the Sacramento River Forecast Center Hydrologic Model and the modified Stanford Watershed Model. However, the modified Stanford Watershed Model was selected for use in the NWSRFS package.

1.4 The USDAHL-74 Model

The USDAHL-74 Model [Holtan, et al., 1974], developed by the United States Department of Agriculture, Agricultural Hydrograph Laboratory, is designed to serve the purposes of agricultural watershed engineering. The primary emphasis is placed on separating out the details of events that occur during the runoff process as a basis for planning the engineering structures and procedures that will control the times, routes, and amounts of water flow. The entire system of watershed hydrology is reduced to a predictable pattern of physical probabilities that will account for the dispersion of water and its subsequent concentration in channel systems.

Soils on each watershed are grouped by land capability classes to form hydrologic response zones for computing infiltration, evapotranspiration, and overland flow. Daily status of soil moisture and increments of water movements in four layers of each zone, considering characteristics of soil, are computed. Crop growth index is computed as a function of current temperature and adjusted to reflect evapotranspiration.

INPUT DATA:

1. Precipitation Input

    - Rainfall data.
    - Snowfall is separately stored

2. Evaporation Data

    - Weekly averages of daily pan evaporation.

3. Temperature

    - Weekly average of daily mean temperatures.

4. Watershed

    1) Areas
    2) Zoning

        - Number of zones.
        - Percent area distribution of the zones in the watershed.
        - Average length of flow on the zone.

4. <u>Watershed (contd)</u>

  2) Zoning (contd)

- Slope of the zone.
- Constant rate of infiltration after prolonged wetting.
- Depth of "A" horizon in agricultural soils or topsoil.
- Depth of aerated well drained soil including topsoil.

3) Soil Characteristics

- G   .   — Percent of topsoil depth drained by gravity (0.0 ~ 0.3 bar tension).

- AWC   — Percent of topsoil depth drained by plants (0.5 ~ 15 bar tension).

    (<u>Note</u>: G + AWC = S, total moisture capacities at 15 bar tension.

- ASM   — Percent of topsoil depth holding water at the beginning of calculation period. This is less than S.

- % Cracks   — Percent of topsoil depth subject to cracking. Cracking is estimated from ratio of bulk density at field capacity to bulk density when air is dry.

    (<u>Note</u>: The same parameters must be also provided for soil profile below the topsoil.)

4) Land Use and Tillage

- Number of crops or land use.
- Percent of the zone in the crop.
- Basal area of vegetation used as an index of surface-connected porosity, the infiltration capacity in inches per hour per $(inch)^{1.4}$ of available storage in the surface layer of the "A" horizon .
- Volume of depressions that would store rainfall until it infiltrates.

4. Watershed (contd)

    4) Land Use and Tillage (contd)

- Ratio of maximum evapotranspiration amount to maximum evaporation for a year.

- Root depth of crop.

- Temperature above which evapotranspiration of crop is impaired.

- Temperature below which evapotranspiration of crop does not function.

- Tillage code (plowing, planting, cultivating and harvesting) and date of the tillage practice.

- Percent reduction of an average value for a year in evapotranspiration of the tillage practice.

    5) Deep Groundwater Recharge

- Deep percolation rate which does not show up in the recession curve.

    6) Initial Snow Cover

- The water equivalent of the amount of snow covering the ground at beginning of calculation period.

5. Routing

    1) Channel Routing

- Calculation time interval desired for channel routing.

- Rate of channel flow at the beginning of the calculation period.

- Channel routing coefficient (M_c; $\Delta S = M_c \Delta q$ where ΔS and Δq are the storage increment and flow rate increment, respectively).

5. Routing (contd)

   2) Subsurface

- Maximum rates of flow associated with each logarithmic linear segment of the recession curve except the channel flow segment.

- Routing coefficient of the segment, not including the channel.

   3) Number of routing coefficients including channel and subsurface flow.

   4) Cascading

- Percent subsurface flow from zones above the alluvium which does not cascade the alluvium, but goes directly to the channels.

- Percent overland flow which cascades the succeeding zone.

- Flow which does not cascade sequentially, but goes either to the channel or alluvium.

ROUTING INVERVAL: Daily.

PROCESS EMULATED:

1. Snowmelt: Calculation is accomplished by an empircal equation containing only 3 factors: temperature, shading and rain on snow.

2. Evapotranspiration: Evapotranspiration potentials are estimated by coefficients applied to pan-evaporation data, considering soil moisture content and crop growth. The temperature is designed to individualize plant growth estimates.

3. Infiltration: Infiltration capacity is a function of soil moisture in the surface layer, vegetation factor, and the constant rate of infiltration after prolonged wetting. Infiltration is limited to an infiltration capacity.

4. Hydrogeology: The percolation from the given layer to the next layer is computed as a function of free-water content in the given layer and estimates of maximum downward percolation rate which is the sum of the maximum lateral flow rate experienced

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in the next layer and the maximum rate of groundwater recharge. Calculation for frozen ground is provided.

5. Overland Flow: A percentage of rainfall in excess of infiltration from each zone is designated to cascade across the subsequent soil zone, with the remainder, if any, allocated to the alluviums or directly to channel flow.

6. Routing

    a. Overland Flow: It is computed by an adaptation of the continuity equation based on turbulent flow.

    b. Channel and Subsurface Flow: They are routed through simultaneous solutions of the continuity equation and a storage function (storage-flow rate relationship). Storage coefficients are determined by a slope for each straight-line segment of the recession curve on semi-logarithmic paper.

1.5   A Rainfall-Runoff Simulation Model for Estimation of Flood Peaks
       for Small Drainage Basins

A parametric model is developed by Dawdy et al. [1972] to simulate flood volume and peak rates of runoff with data from a point rainfall gage and data on daily potential for small drainage areas. The model is based on bulk parameter approximations to the physical laws governing infiltration, soil moisture accretion and depletion, and surface streamflow.

The model deals with three components of the hydrologic cycle: antecedent moisture accounting, infiltration, and surface runoff. The antecedent moisture accounting component is a more detailed version of the antecedent-precipitation index (API) which is designed to determine the initial infiltration rate. The infiltration component uses the Philip infiltration equation. Surface routing is based on a time-discharge histogram and instantaneous unit hydrograph approach.

The model requires a time-discharge histogram and eight parameters. The routine to determine optimum parameters values is provided. The objective function is the sum of the squared derivations of the logarithms of peak flows, storm volumes, or some combination of both. Description of input parameters and characteristics of the model are not given here since the model does not have the capability of producing continuous runoff results.

1.6   Urban Storm Water Runoff Model "Storm"

The original version of the model is developed by Water Resources
Engineers, Inc., of Walnut Creek, California. The program was modified
by the Hydrologic Engineering Center [1975] to include computations for the
quality and quantity of runoff from nonurban areas, snowfall and snowmelt,
and land surface erosion for urban and nonurban watersheds. The purpose
of the analysis is to aid in the selection of storage and treatment facilities
to control the quantity and quality of urban storm water runoff and land sur-
face erosion. Land surface erosion for urban and nonurban areas is computed
in addition to the basic water quality parameters and settleable solids: bio-
chemical oxygen demand (BOD), total nitrogen (N), and orthophosphate (PO_4).
The model considers the interaction of seven storm water components:

- Precipitation and air temperature for rainfall/snowmelt.

- Runoff.

- Pollutant accumulation.

- Land surface erosion.

- Treatment rates.

- Storage

- Overflow from the storage/treatment system.

1.7   Other Watershed Models

Leaf and Brink [1973] described a model for simulating snowmelt in central Colorado subalpine watersheds. Snowmelt over an area is described in terms of combinations as aspect, slope, elevation, and forest cover composition and density. Leaf and Brink [1973] also described an expanded version of the snowmelt model. It is designed to simulate the total water balance on a continuous, year-round basis, and to compile the results from individual hydrologic subunits into a "composite overview" of an entire watershed. The model has been designed to simulate watershed management practices and their resultant effects on the behavior of hydrologic systems.

APPENDIX A.2

PLOTS OF WATERSHED PARAMETER SENSITIVITY RESULTS

The watershed parameter sensitivity values given in Table 4-1 are presented in graph form in Figures A.2-1 through A.2-7.
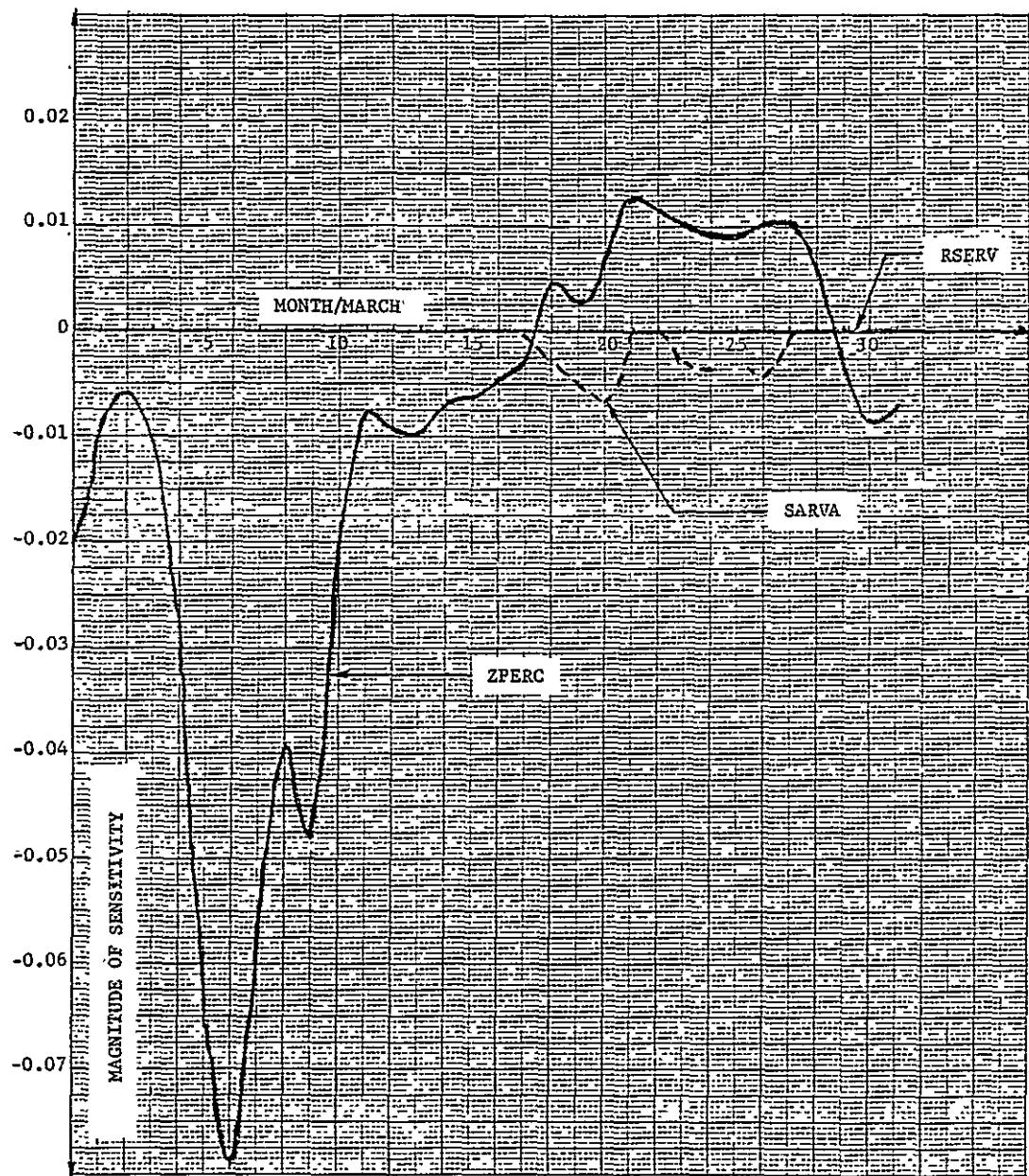
Figure A.2-1. Sensitivity Analysis.
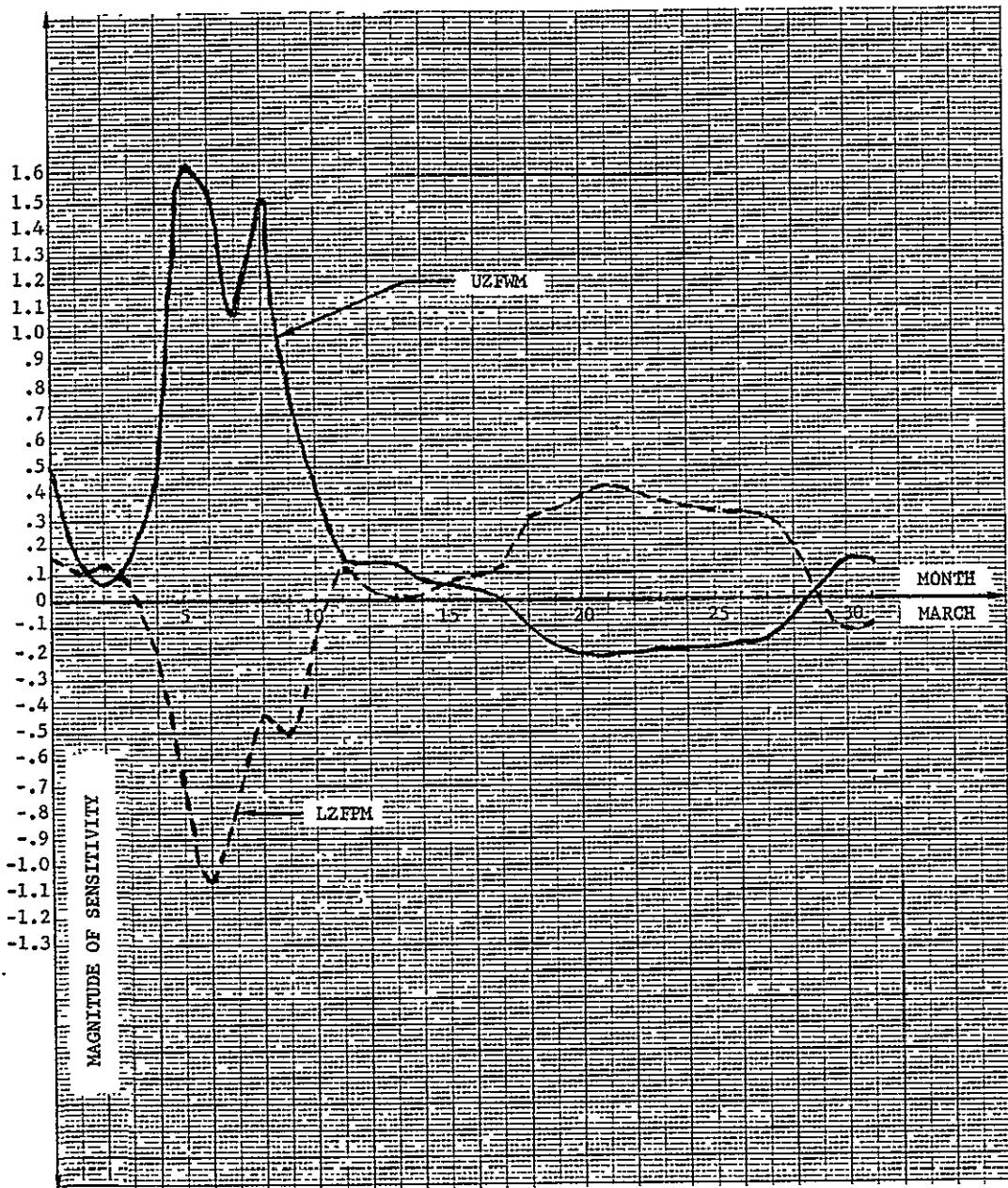
Figure A. 2-2. Sensitivity Analysis (contd).
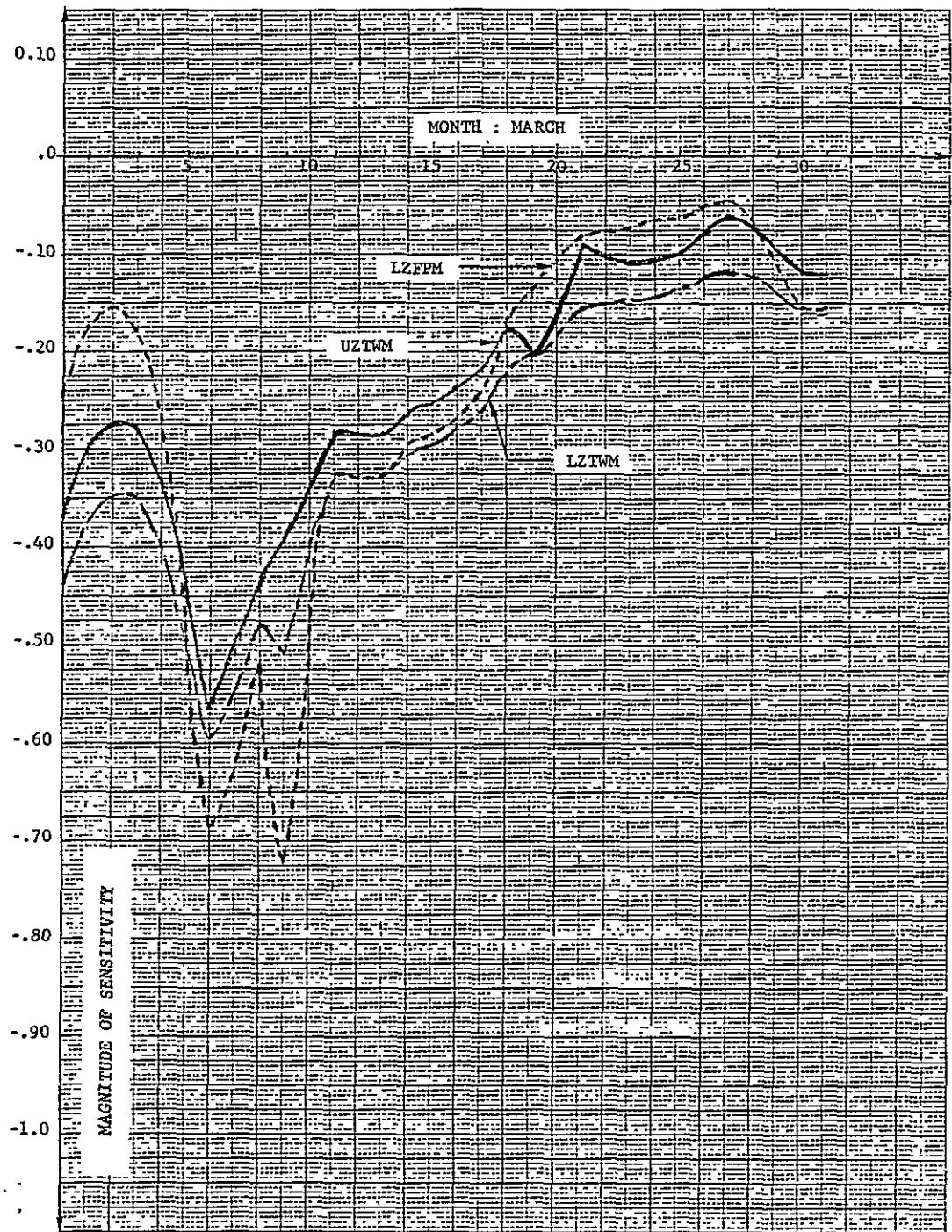
Figure A.2-3. Sensitivity Analysis (contd).
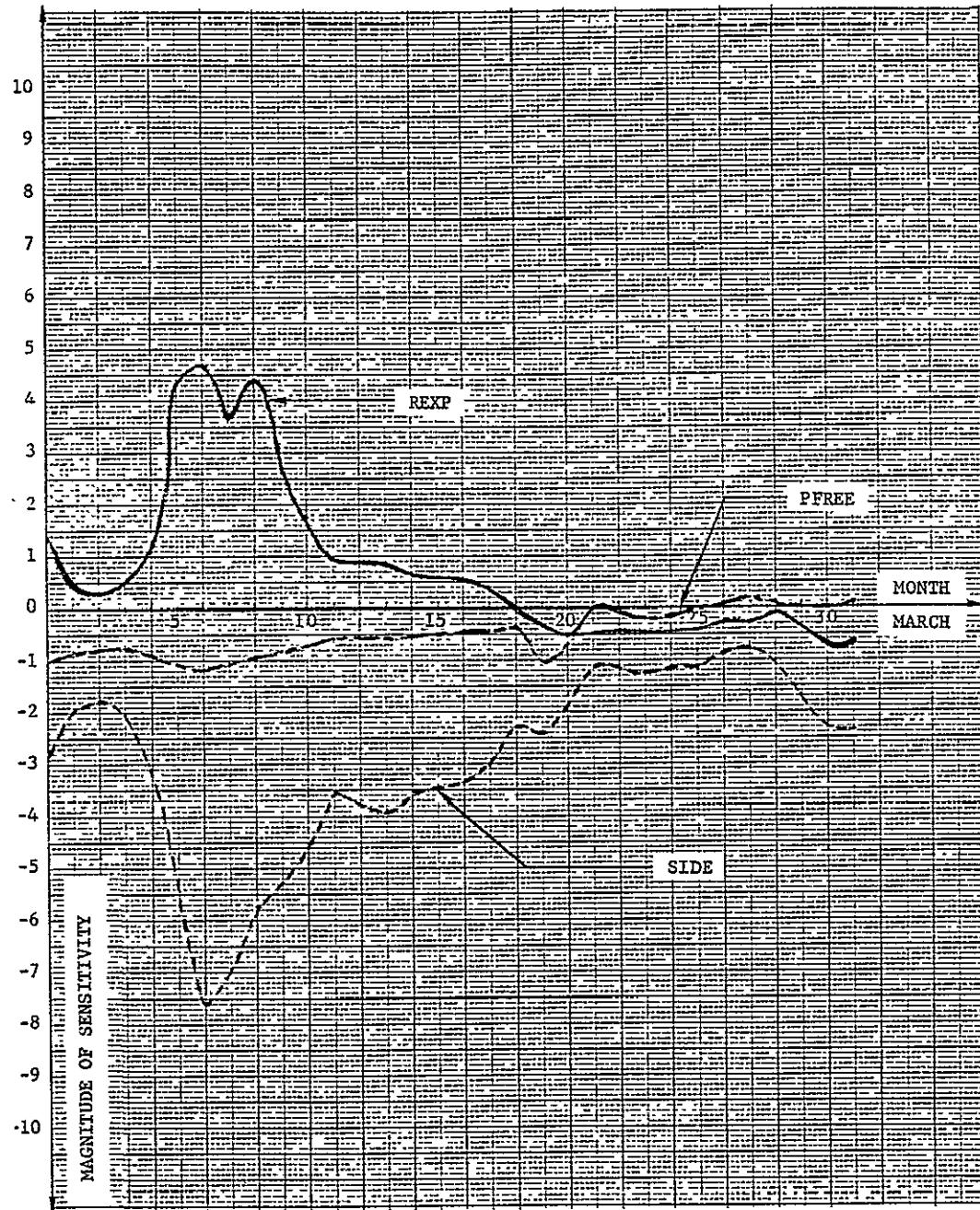
Figure A.2-4. Sensitivity Analysis (contd).
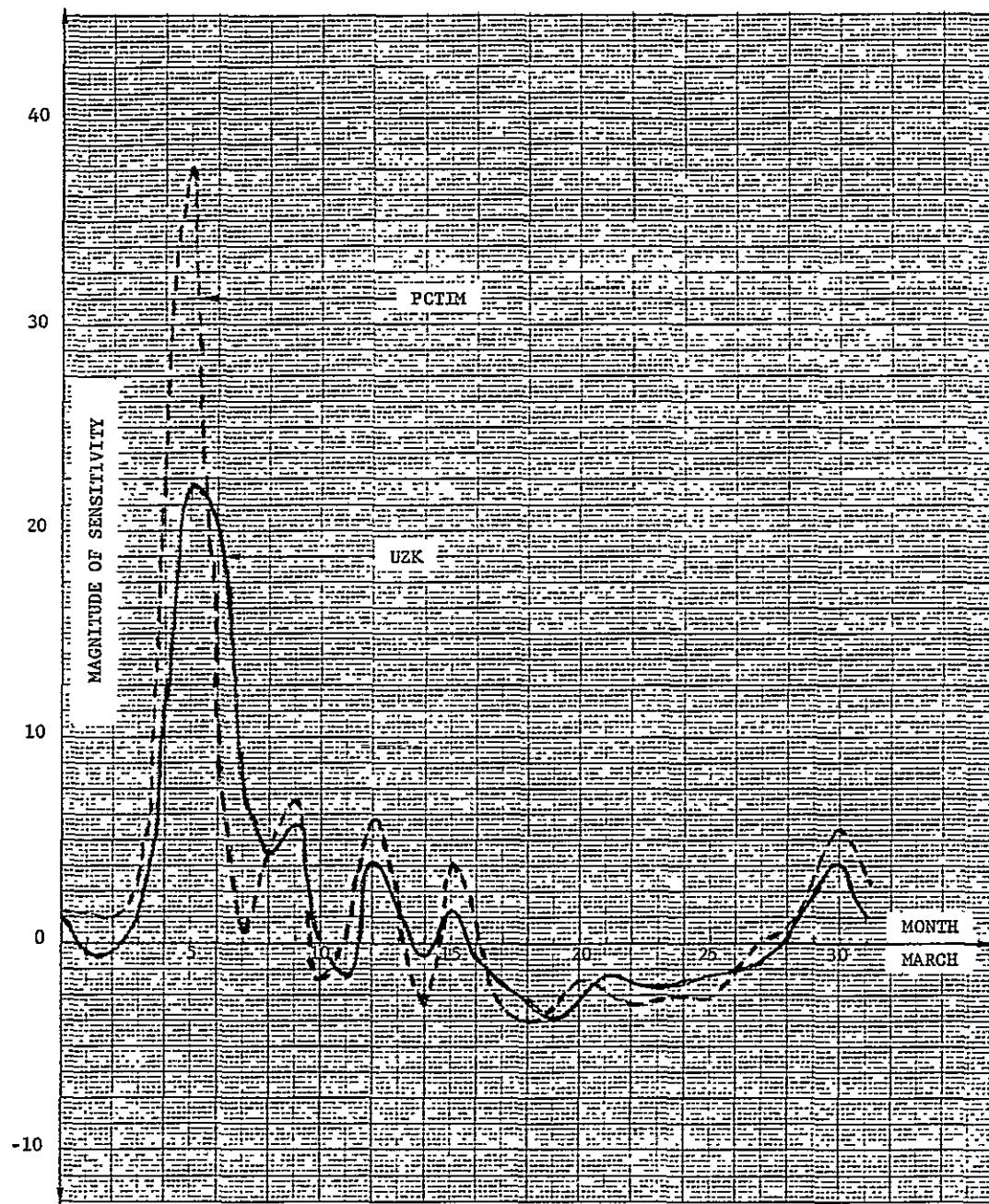
Figure A.2-5. Sensitivity Analysis (contd).
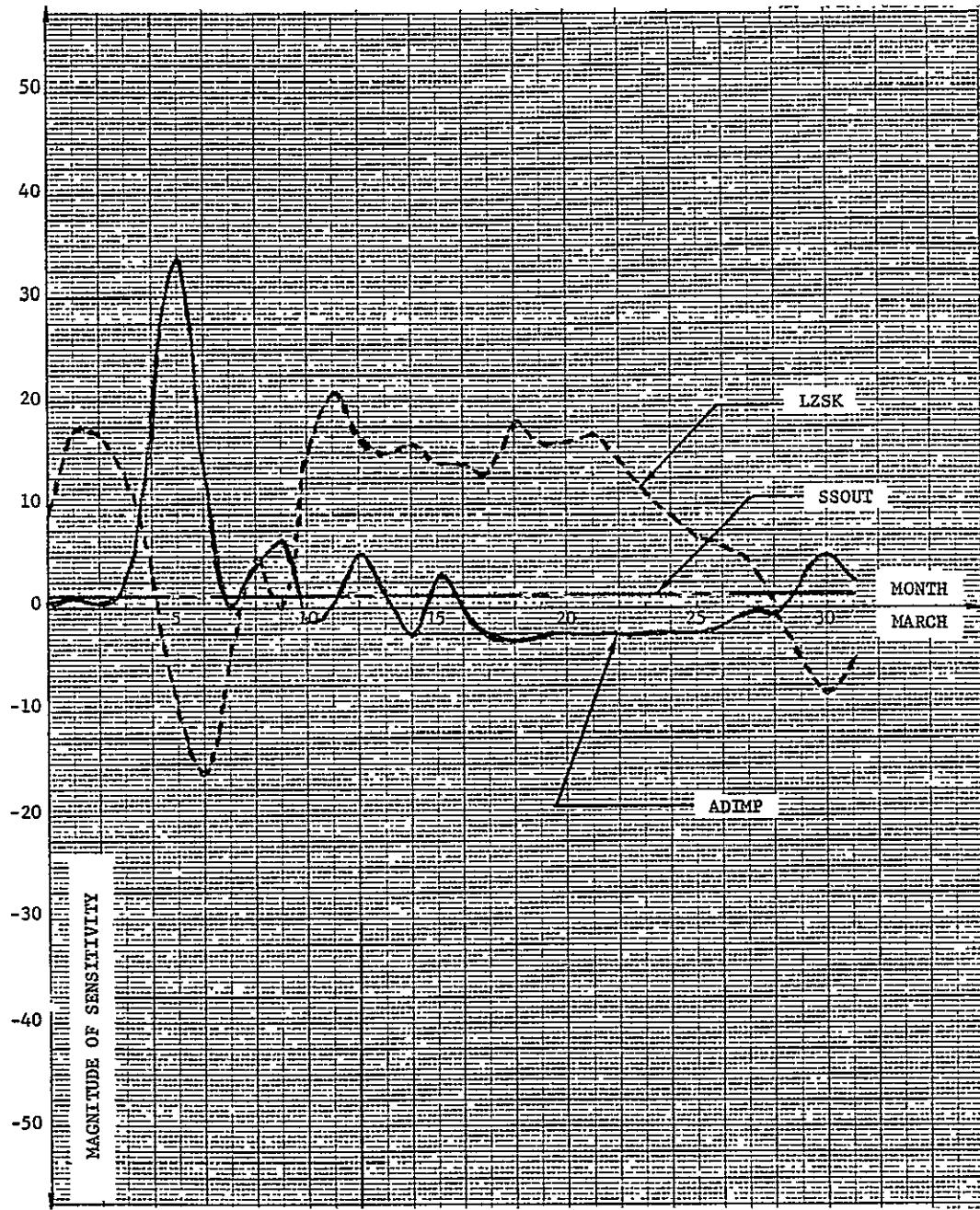
Figure A.2-6. Sensitivity Analysis (contd).
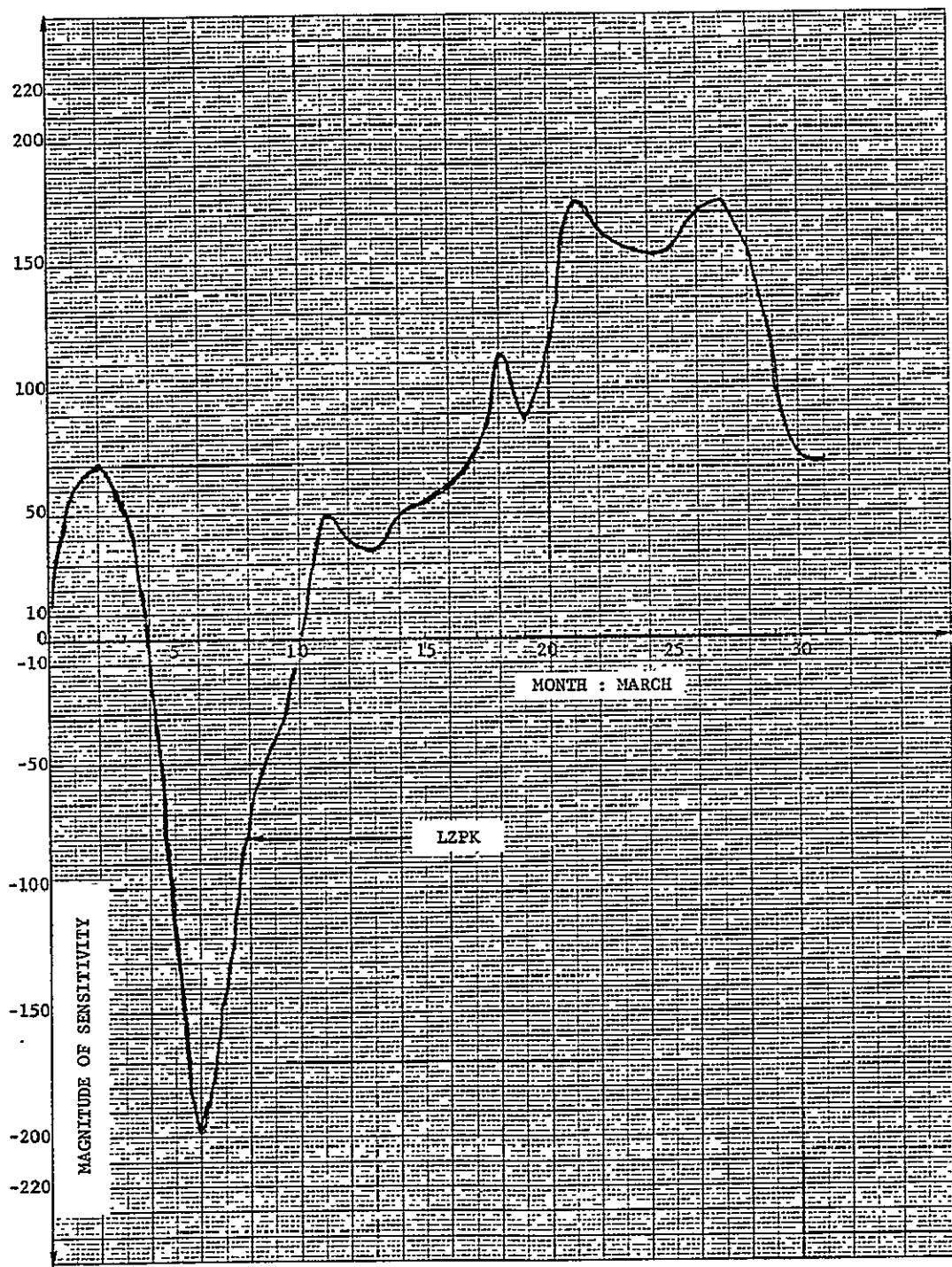
Figure A.2-7. Sensitivity Analysis (contd).

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APPENDIX B

MAJOR U.S. HYDROPOWER FACILITIES

APPENDIX B

MAJOR U.S. HYDROPOWER FACILITIES

Hydropower facilities with at least 100 MW installed capacity are distributed throughout the country (1970) as shown by Figure B-1; potential sites are indicated on Figure B-2. There are many more smaller units but it is convenient to take 100 MW as a breakpoint for this study. (About one-quarter of total capacity is thus excluded.) Concentrations in the Pacific Northwest, Northern California, the Tennessee Valley, Lower Mississippi Drainage (South Central), and the Upper Missouri and Colorado River Basins are clear. Table B-1 lists the plant names, installed capacities, and ownership for existing and under construction plants. The preponderance of Federal ownership, particularly of the larger capacities, is to be noted. The Federal system in the Columbia River Basin constitutes about one-half the total hydropower in the Basin and about one-quarter of the total hydropower in the country. The Columbia River Basin is shown in some detail on Figure B-3, the TVA on Figure B-4, the Central Valley·Project of California on Figure B-5, the.Colorado River Basin on Figure B-6, and the Upper Missouri Basin on Figure B-7.

As of January 1972, 53,400 MW of installed capacity representing 29.9% of total potential (including Alaska and Hawaii) were located on 1463 sites. Federal ownership totaled 33,600 MW. As a percentage of total electrical plant, hydroelectric is now about 15% and slowly declining as more thermal plants are built. However, hydropower is still the major source in the Pacific Northwest. A large number of plants are run of the river or pondage types and are often non-Federal and thus licensed by the Federal Power Commission (FPC). Very detailed listings giving drainage, river basin, river, plant name and site, installed capacity, average annual energy generated, usable power storage, and gross head can be found in Reference B.1. Additional operational and descriptive material are available for each plant from the Planning Status and Evaluation Reports of the FPC and the Annual Operating Plans put out by the Bureau of Reclamation (BR), Corps of Engineers (CE), and Tennessee Valley Authority (TVA).

B.1   "Hydroelectric Power Resources of the United States," Federal Power Commission, Jan. 1972.

Capacity Mw	Existing	Under Construction
100 - 499	▪	▫
Over 499	▣	□

Note: Excludes all reversible capacity and capacity in plants or plant additions of less than 100 mw.
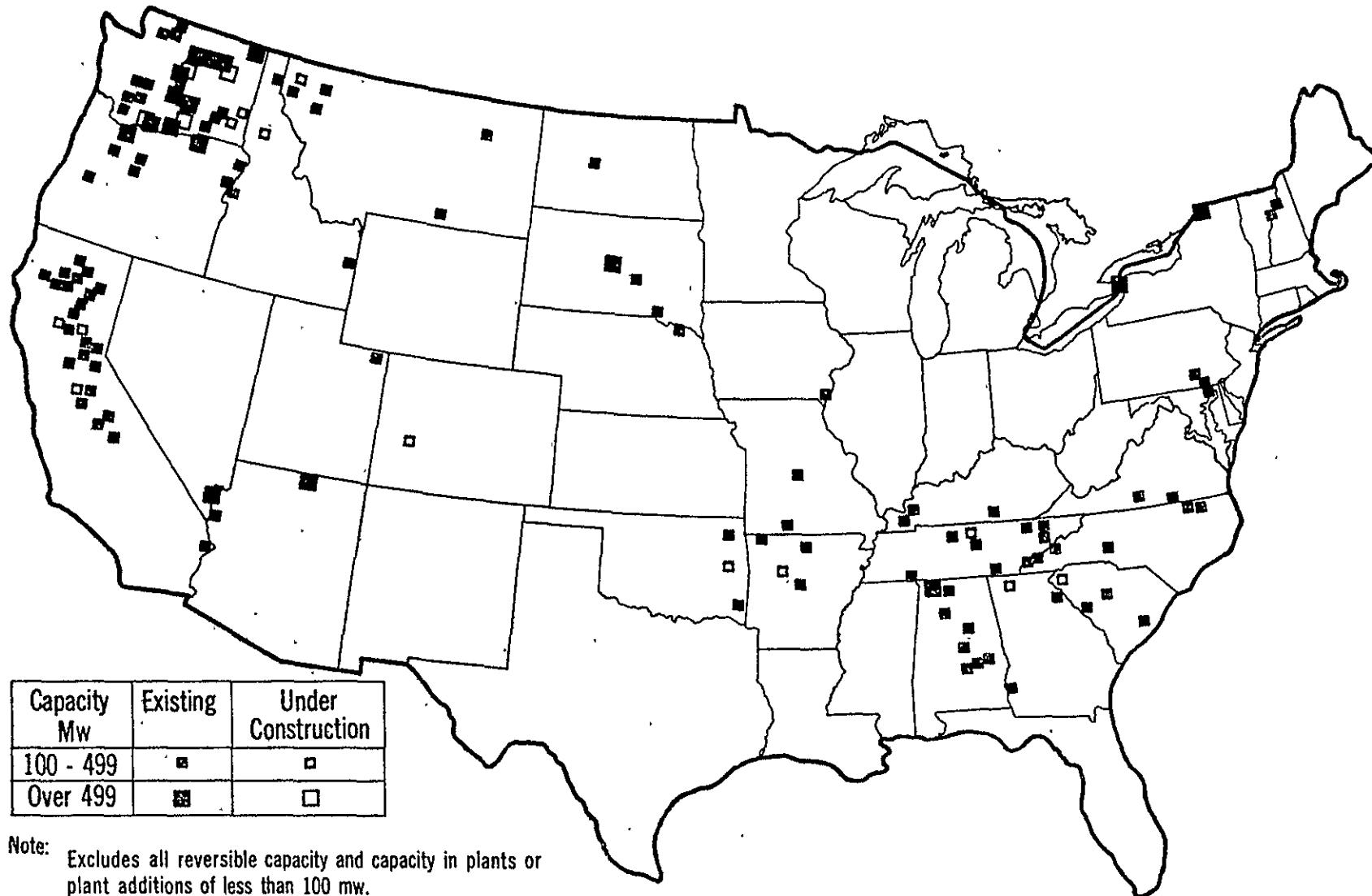
Figure B-1. Conventional Hydroelectric Capacity.
Existing and Under Construction, December 31, 1970.

Capacity, Mw	Expanded	New
100 - 499	▣	▫
Over 499	■	☐
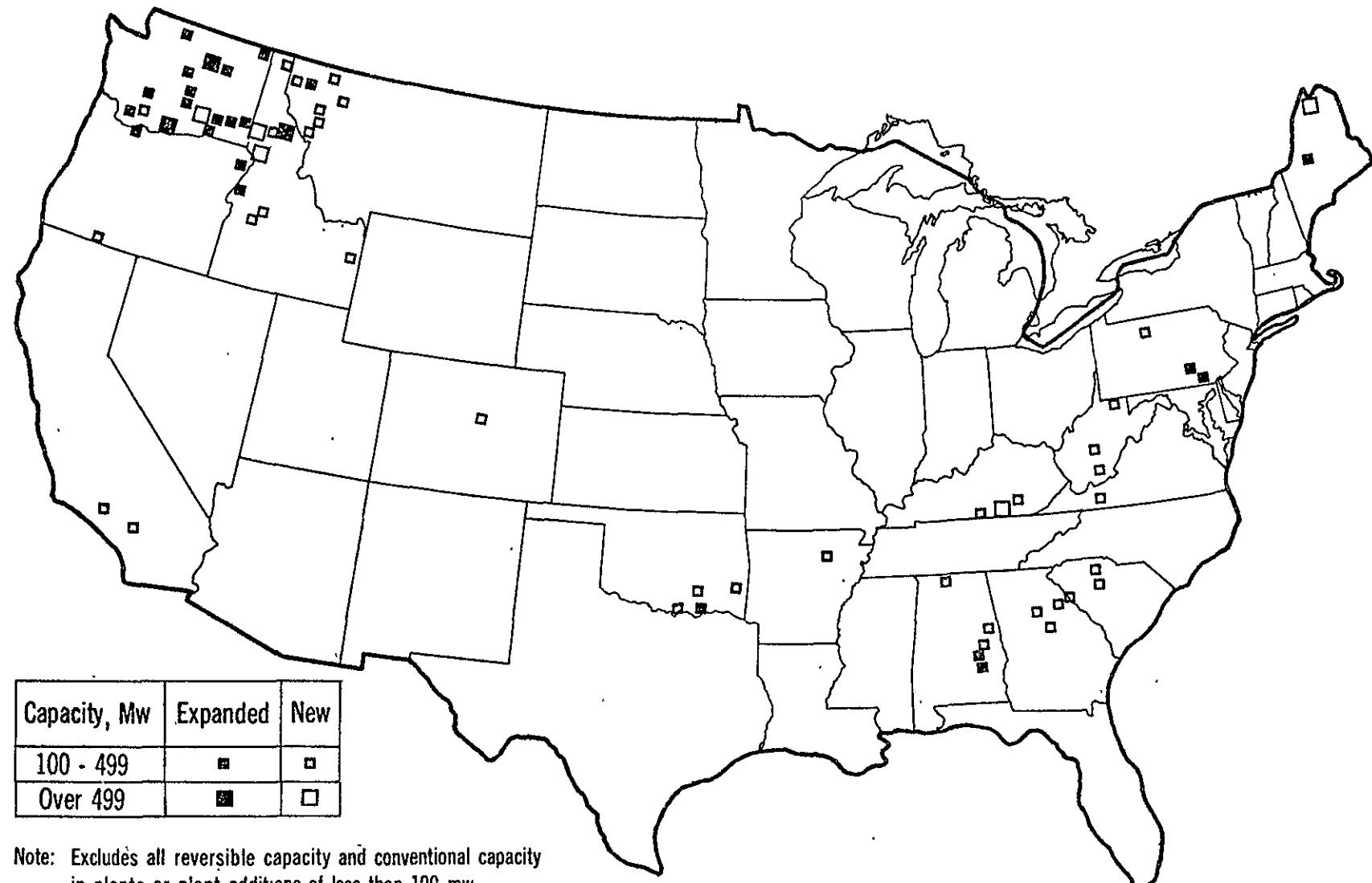
Note: Excludes all reversible capacity and conventional capacity in plants or plant additions of less than 100 mw.

Figure B-2. Conventional Hydroelectric Capacity.
New and Expanded — Projected to 1990.

Table B-1. Conventional Hydroelectric Capacity Existing and Under Construction as of December 31, 1970.

(Listed projects have installations of 100 MW or more)

Plant Name and Location	River	Owner	Installed Capacity, MW	
			Existing	Under Construction
NORTHEAST REGION				
Moore, N.H.	Connecticut	New England Power Co	140	
Comerford, N.H.	Connecticut	New England Power Co	140	
Robert Moses, N.Y.	St. Lawrence	Power Auth. of State of New York	912	
Niagara, N.Y.	Niagara	Power Auth. of State of New York	1,954	
Holtwood, Pa.	Susquehanna	Pa. Power and Light Co	107	
Safe Harbor, Pa.	Susquehanna	Safe Harbor Water Power Corp	227	
Conowingo, Md.	Susquehanna	Susquehanna Power and Phila. Elec. Pwr.	475	
Subtotal			3,955	
Installations of less than 100 MW			1,905	
Total			5,860	
EAST CENTRAL REGION				
Smith Mountain, Va.*	Roanoke	Appalachian Power Co	300	
Installations of less than 100 MW			718	61
Total			1,018	61
SOUTHEAST REGION				
Roanoke Rapids, N.C.	Roanoke	Virginia Electric and Power Co	100	
Gaston, N.C.	Roanoke	Virginia Electric and Power Co	178	
John H. Kerr, Va.	Roanoke	Corps of Engineers	204	
Cowans Ford, N.C.	Catawba	Duke Power Co	350	
Saluda, S.C.	Saluda	South Carolina Electric and Gas Co.	130	79
Pinopolis, S.C.	Santee-Cooper	South Carolina Public Serv. Authority	133	
Clark Hill, S.C.	Savannah	Corps of Engineers	280	
Keowee, S.C.	Keowee	Duke Power Co		140
Walters, N.C.	Pigeon	Carolina Power and Light Co	108	
Kentucky, Ky.	Tennessee	Tennessee Valley Authority	170	
Pickwick Landing, Tenn.	Tennessee	Tennessee Valley Authority	216	
Wilson, Tenn.	Tennessee	Tennessee Valley Authority	630	
Wheeler, Tenn.	Tennessee	Tennessee Valley Authority	356	
Chickamauga, Tenn.	Tennessee	Tennessee Valley Authority	108	
Watts Bar, Tenn.	Tennessee	Tennessee Valley Authority	150	
Norris, Tenn.	Clinch	Tennessee Valley Authority	101	
Calderwood, Tenn.	Little Tennessee	Tapoco, Inc.	122	
Cheoah, N.C.	Little Tennessee	Tapoco, Inc.	110	
Fontana, N.C.	Little Tennessee	Tennessee Valley Authority	225	
Fort Loudoun, Tenn.	Tennessee	Tennessee Valley Authority	131	
Douglas, Tenn.	French Broad	Tennessee Valley Authority	112	
Cherokee, Tenn.	Holston	Tennessee Valley Authority	120	
Barkley, Ky.	Cumberland	Corps of Engineers	130	
Old Hickory, Tenn.	Cumberland	Corps of Engineers	100	
Center Hill, Tenn.	Caney Fork	Corps of Engineers	135	
Cordell Hull, Tenn.	Cumberland	Corps of Engineers		100
Wolf Creek, Ky.	Cumberland	Corps of Engineers	270	
Hartwell, Ga.	Savannah	Corps of Engineers	264	
Walter F. George, Ga.	Chattahoochee	Corps of Engineers	130	
Carters, Ga.*	Coosawattee	Corps of Engineers		250
Lewis Smith, Ala.	Black Warrior	Alabama Power Co	158	

Table B-1. Conventional Hydroelectric Capacity Existing and
Under Construction as of December 31, 1970. (contd)

(Listed projects have installations of 100 MW or more)

Plant Name and Location	River	Owner	Installed Capacity, MW	
			Existing	Under Construction
SOUTHEAST REGION—Continued				
Martin, Ala...............	Tallapoosa...........	Alabama Power Co...............	154	....
Walter Bouldin, Ala.........	Coosa...............	Alabama Power Co...............	225	....
Jordan, Ala...............	Coosa...............	Alabama Power Co...............	100	....
Logan Martin, Ala..........	Coosa...............	Alabama Power Co...............	128	....
Lay Dam, Ala..............	Coosa...............	Alabama Power Co...............	177	....
Subtotal.......			6,005	569
Installations of less than 100 MW........			3,234	186
Total........			9,239	755
WEST CENTRAL REGION				
Fort Peck, Mont............	Missouri............	Corps of Engineers...............	165	....
Garrison, N. Dak...........	Missouri............	Corps of Engineers...............	400	....
Oahe, S. Dak..............	Missouri............	Corps of Engineers...............	595	....
Big Bend, S. Dak...........	Missouri............	Corps of Engineers...............	468	....
Fort Randall, S. Dak........	Missouri............	Corps of Engineers...............	320	....
Gavins Point, Nebr.........	Missouri............	Corps of Engineers...............	100	....
Keokuk, Iowa..............	Mississippi...........	Union Electric Co................	125	....
Osage (Bagnell), Mo........	Osage...............	Union Electric Co................	172	....
Subtotal........			2,345	....
Installations of less than 100 MW........			867	27
Total........			3,212	27
SOUTH CENTRAL REGION				
Dardanelle, Ark............	Arkansas............	Corps of Engineers...............	124	....
Ozark, Ark................	Arkansas............	Corps of Engineers...............		100
Robert S. Kerr, Okla........	Arkansas............	Corps of Engineers...............		110
Beaver, Ark................	White...............	Corps of Engineers...............	112	....
Bull Shoals, Ark............	White...............	Corps of Engineers...............	340	....
Table Rock, Mo............	White...............	Corps of Engineers...............	200	....
Broken Bow, Okla..........	Mountain Fork.......	Corps of Engineers...............	100	....
Markham Ferry, Okla.......	Grand..............	Grand River Dam Authority.......	108	....
Subtotal........			984	210
Installations of less than 100 MW........			1,196	145
Total........			2,180	355
WEST REGION				
Trinity, Cal................	Trinity..............	Bureau of Reclamation...........	106	....
Judge Francis Carr, Cal.....	Clear Creek..........	Bureau of Reclamation...........	141	....
Folsom, Cal...............	American............	Bureau of Reclamation...........	186	12
Auburn, Cal...............	N. Fk. American.....	Bureau of Reclamation...........		300
White Rock, Cal...........	S. Fk. American......	Sacramento Municipal Utility Dist..	190	....
Camino, Cal...............	S. Fk. American......	Sacramento Municipal Utility Dist..	142	....
Middle Fork American, Cal..	M. Fk. American.....	Placer County Water Agency.......	110	....
Jaybird, Cal...............	Silver Creek.........	Sacramento Municipal Utility Dist..	133	....
New Colgate, Cal...........	N. Yuba............	Yuba County Water Agency.......	284	....
Edward Hyatt, Cal.*........	Feather.............	California Dept. of Water Resources.	351	....
Poe, Cal..................	N. Fk. Feather.......	Pacific Gas and Electric Co........	124	....
Rock Creek, Cal............	N. Fk. Feather.......	Pacific Gas and Electric Co........	113	....
Belden, Cal................	N. Fk. Feather.......	Pacific Gas and Electric Co........	118	....
Caribou No. 2, Cal.........	N. Fk. Feather.......	Pacific Gas and Electric Co........	110	....
Spring Creek, Cal..........	Spring Creek........	Bureau of Reclamation............	150	....

Table B-1. Conventional Hydroelectric Capacity Existing and
Under Construction as of December 3, 1970. (contd)

(Listed projects have installations of 100 MW or more)

Plant Name and Location	River	Owner	Installed Capacity, MW	
			Existing	Under Construction
WEST REGION—Continued				
Shasta, Cal................	Sacramento..........	Bureau of Reclamation............	420	
Pit No. 5, Cal..............	Pit...................	Pacific Gas and Electric Co........	134	
Pit No. 7, Cal..............	Pit...................	Pacific Gas and Electric Co........	104	
James B. Black, Cal.........	Pit...................	Pacific Gas and Electric Co........	155	
New Melones, Cal..........	Stanislaus............	Corps of Engineers...............................		300
D. R. Holm, Cal...........	Cherry Creek........	San Francisco Utilities Commission..	135	
New Don Pedro, Cal........	Tuolumne...........	Turlock Modesto Irrigation District.	137	
Haas, Cal..................	N. Fk. Kings.........	Pacific Gas and Electric Co........	135	
Big Creek No. 3, Cal........	San Joaquin.........	Southern California Edison Co.....	107	
Mammoth Pool, Cal........	San Joaquin.........	Southern California Edison Co.....	129	
Parker, Cal................	Colorado............	Bureau of Reclamation............	120	
Davis, Ariz................	Colorado............	Bureau of Reclamation............	225	
Glen Canyon, Ariz..........	Colorado............	Bureau of Reclamation............	950	
Hoover, Ariz.-Nev..........	Colorado............	Bureau of Reclamation............	1,340	
Morrow Point, Colo.........	Gunnison............	Bureau of Reclamation............	60	60
Yellowtail, Mont...........	Bighorn.............	Bureau of Reclamation............	250	
Kerr, Mont................	Flathead.............	Montana Power Co................	168	
Hungry Horse, Mont........	S. Fk. Flathead.......	Bureau of Reclamation............	285	
Libby, Mont...............	Kootenai............	Corps of Engineers...............................		420
Hells Canyon, Oreg.........	Snake...............	Idaho Power Co..................	392	
Oxbow, Oreg..............	Snake...............	Idaho Power Co..................	190	
Brownlee, Idaho...........	Snake...............	Idaho Power Co..................	360	
Palisades, Idaho............	Snake...............	Bureau of Reclamation............	114	
Flaming Gorge, Utah.......	Green...............	Bureau of Reclamation............	108	
Dworshak, Idaho...........	N. Fk. Clearwater....	Corps of Engineers...............................		400
Priest Rapids, Wash.........	Columbia............	Grant County PUD No. 2.........	788	
Wanapum, Wash...........	Columbia............	Grant County PUD No. 2.........	831	
Wells, Wash...............	Columbia............	Douglas County PUD No. 2........	774	
Chief Joseph, Wash.........	Columbia............	Corps of Engineers...............	1,024	
Grand Coulee, Wash........	Columbia............	Bureau of Reclamation............	1 2,066	3,600
Boundary, Wash............	Pend Oreille.........	Seattle Dept. of Lighting...........	551	
Cabinet Gorge, Idaho.......	Clark Fork...........	Washington Water Power Co.......	200	
Noxon Rapids, Mont........	Clark Fork...........	Washington Water Power Co.......	283	
Gorge, Wash..............	Skagit...............	Seattle Dept. of Lighting...........	134	
Diablo, Wash..............	Skagit...............	Seattle Dept. of Lighting...........	120	
Ross, Wash................	Skagit...............	Seattle Dept. of Lighting...........	360	
Mayfield, Wash............	Cowlitz.............	City of Tacoma..................	122	
Mossyrock, Wash...........	Cowlitz.............	City of Tacoma..................	300	
Rock Island, Wash..........	Columbia............	Chelan County PUD No. 1.........	212	
Rocky Reach, Wash........	Columbia............	Chelan County PUD No. 1........	712	502
John Day, Wash............	Columbia............	Corps of Engineers...............	1,890	270
The Dalles, Wash...........	Columbia............	Corps of Engineers...............	1,119	688
Bonneville, Oreg...........	Columbia............	Corps of Engineers...............	518	
McNary, Oreg.............	Columbia............	Corps of Engineers...............	980	
Merwin, Wash.............	Lewis...............	Pacific Power and Light Co........	135	
Yale, Wash................	Lewis...............	Pacific Power and Light Co........	108	
Swift No. 1, Wash..........	Lewis...............	Pacific Power and Light Co........	204	
Pelton, Oreg...............	Deschutes............	Portland General Electric Co.......	108	
Round Butte, Oreg.........	Deschutes............	Portland General Electric Co.......	247	
Ice Harbor, Wash..........	Snake...............	Corps of Engineers...............	270	
Lower Monumental, Wash...	Snake...............	Corps of Engineers...............	405	
Little Goose, Wash.........	Snake...............	Corps of Engineers...............	405	
Lower Granite, Wash.......	Snake...............	Corps of Engineers...............................		405

LEGEND

DAM
RESERVOIR
POWER PLANT

MAJOR RESERVOIR AND POWER PROJECTS
EXISTING AND UNDER CONSTRUCTION

MAP NO.	PROJECT	OWNERSHIP
1	Mossyrock	Non-federal
2	Swift No. 1	Non-federal
3	Bonneville	Federal
4	The Dalles	Federal
5	Round Butte	Non-federal
6	John Day	Federal
7	McNary	Federal
8	Ice Harbor	Federal
9	Lower Monumental	Federal
10	Little Goose	Federal
11	Lower Granite	Federal
12	Dworshak	Federal
13	Hells Canyon	Non-federal
14	Oxbow	Non-federal
15	Brownlee	Non-federal
16	Palisades	Federal
17	Priest Rapids	Non federal
18	Wanapum	Non-federal
19	Rock Island	Non-federal
20	Rocky Reach	Non-federal
21	Wells	Non-federal
22	Chief Joseph	Federal
23	Grand Coulee	Federal
24	Boundary	Non-federal
25	Albeni Falls	Federal
26	Cabinet Gorge	Non-federal
27	Noxon Rapids	Non-federal
28	Kerr	Non federal
29	Hungry Horse	Federal
30	Corra Linn	Canadian
31	Libby	Federal
32	Duncan Lake	Canadian
33	Hugh Keenley Side	Canadian
34	Mica	Canadian

Figure B-3. Map and Profile of Columbia River Basin.
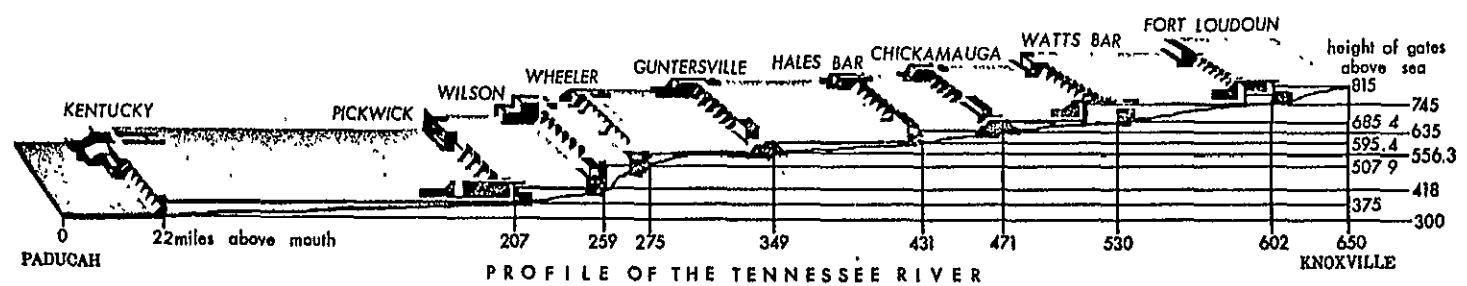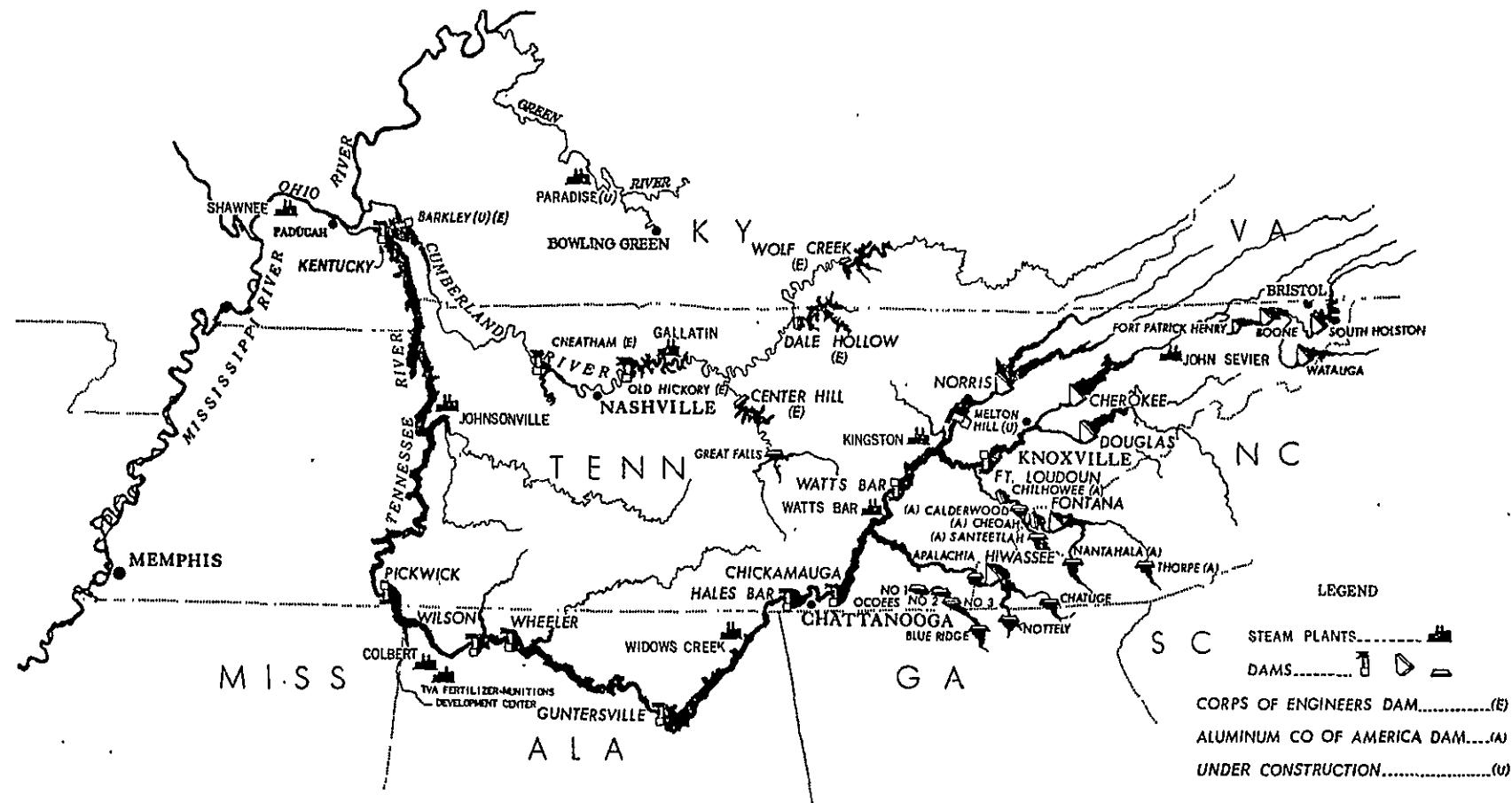
Figure B-4. Tennessee Valley Region.
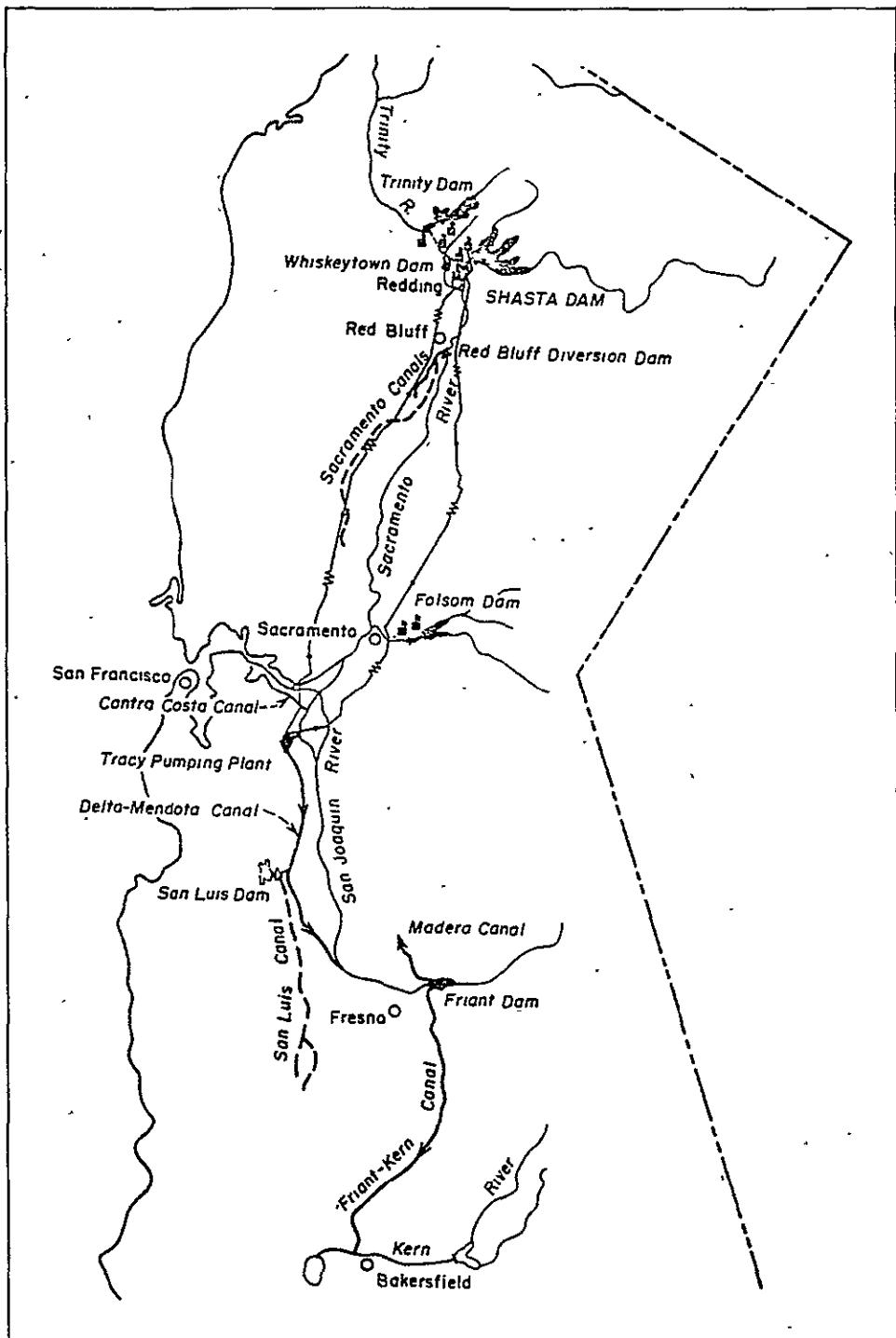
Figure B-5. Central Valley Project of California.
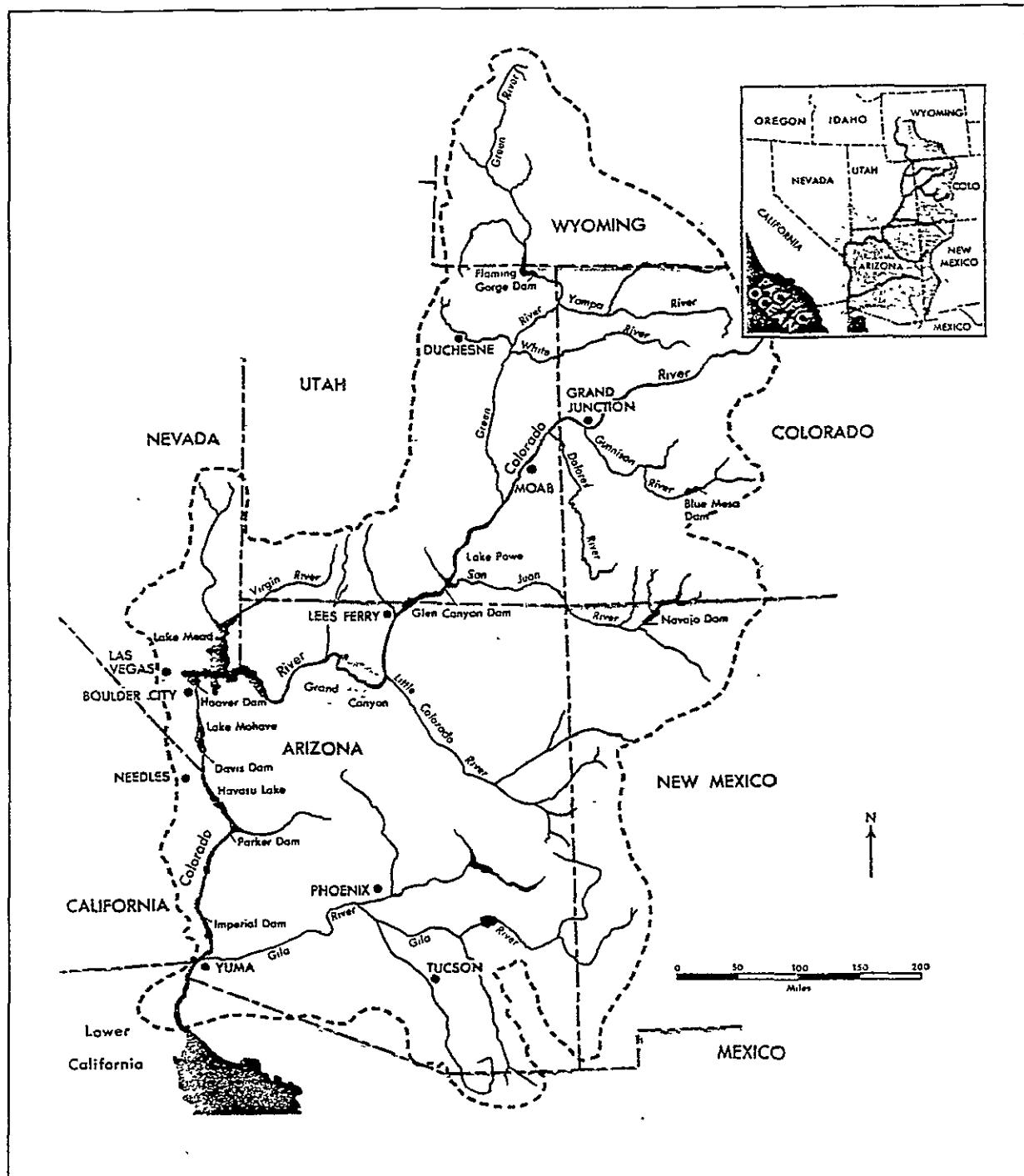
Figure B-6. Colorado River Basin.
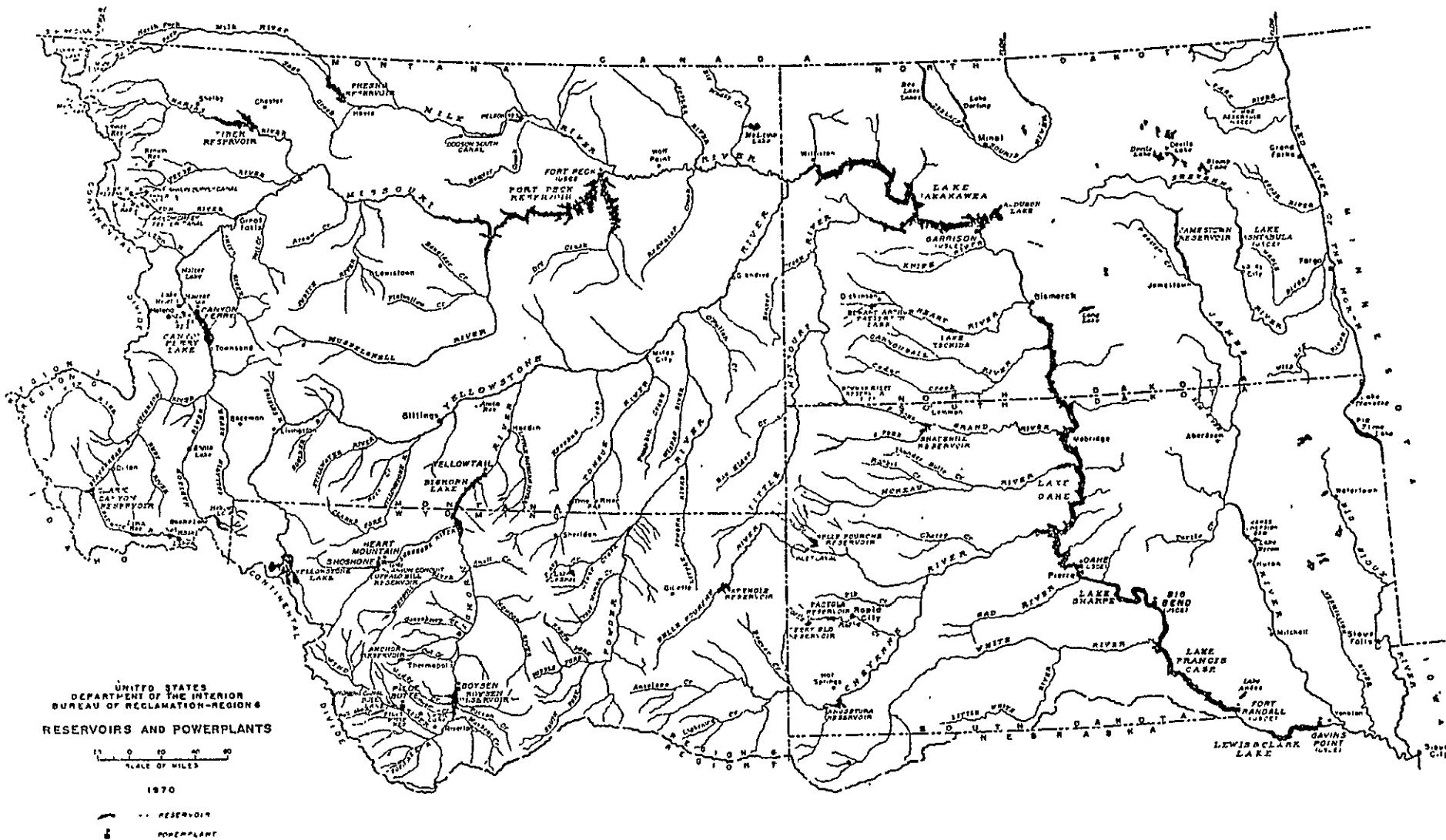
Figure B-7. Upper Missouri Basin.

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APPENDIX C

HYDROPOWER OPERATIONS MODELS

APPENDIX C

HYDROPOWER OPERATIONS MODELS

Hydropower system releases are determined from operations models. As has been indicated in Chapter 7, the complexities of multipurpose, multi-facility systems generally require release decisions to be determined by an optimization model based on some type of mathematical programming. The models must operate effectively in "real time" — that is, a model must always be accessible for updating with new information with a turnaround time no greater than about an hour, and current information as to inflow data is given much more credence than any historical pattern. Of course, if there are gaps in or doubts about current information, advantage should be taken of historical data. The models must be deterministic to take advantage of present information and to be practically applicable to multiple purpose, multiple facility systems.

An overall operations model must be capable of determining both long and short term release policies, as discussed in Chapter 7, and an initial decomposition into submodels usually is made along those lines. Long and short term submodels require corresponding inflow forecasts, and the long term forecast will necessarily be based on historic patterns but is nevertheless, deterministic. Both submodels are periodically updated in accordance with their respective time increments. However, in some cases (Columbia River Basin, for example) the long term model is for the purpose of calculating a critical rule curve based on the "worst" historical data, and a seasonal storage policy is calculated only once a year. The submodels may be of mixed types using different algorithms; however, they tend to be of the same type.

All operating decision models require the use of a digital computer but nevertheless yield only approximate optimal policies, as approximations of one sort or another must be made to enable practical solution techniques. Usually, solutions will improve with iterations of the particular technique used, but at the cost of greater computer time. Practically, all solution techniques which are being developed for operational use will yield similar answers; the differences between them are in the areas of computational time, data requirements and access, extensibility to an enlarged system and to other systems,

and the degree of interplay between model and system manager during the optimization process. These differences can be significant. Common requirements are an on-line capability, an optimization which is constrained by the necessity for continuing operations indefinitely, and the minimization of spilling. Common problems relate to the nonlinearity of hydropower systems and the very high dimensionality (number of state variables, decision variables, and constraints) typical of the water resource optimization problem. In all cases the production of hydropower is to be optimized. Both objective function and constraints will contain nonlinearities, essentially because of power and energy relationships. In some cases the objective function is also nonlinear because of optimization of power revenues and because of a variable power rate structure; however, this is often an unnecessary complication.

The nonlinear penalty type is being developed and used by Bonneville Power Administration (BPA) for the Columbia River Basin in its short period optimization, and is applied to 16 "key" plants in the system. Nonlinear problems with many variables and constraints are very difficult to solve; BPA surmounts this difficulty by declaring many of the constraints "soft" — that is, they may be violated on sufferance of a penalty — and inserting these constraints into the objective function via weighted penalty functions. The problem then becomes practically unconstrained and can be solved by judicious use of gradient methods — e.g., the conjugate gradient method of Fletcher and Reeves. The above technique requires an initial policy which the optimization procedure will improve on. The initial policy taken is derived from their previous experience and is generally good to start with. For good convergence to an optimum the weighting of the penalty functions is all-important. Large weights are needed for constraint satisfaction but small weights are required for rapid convergence. Therefore, a sequence of optimizations is used in which weights progress from small to large values and relative weightings may be varied. BPA says that normally 3 runs on a CDC 6500 at 10 minutes per run will produce satisfactory results. This technique would not be easily applicable for those systems which had a large number of hard constraints — constraints which could not be violated because of legal or other firm agreements. Large weights for these constraints might bring their violation to zero but at the cost of very slow convergence and unfavorable effects on the other penalty terms.

Pure dynamic programming (DP) can only be used for simple systems in which the number of decision and state variables do not exceed two. Computational requirements increase exponentially with increase in the number of variables (and with greater desired accuracies), particularly the high speed computer storage. DP is not used for any of the hydropower systems which would be relevant for this study. It is useful for the study of simple subsystems and is limited only by the requirement that the objective function be separable with respect to its variables.

Incremental DP reduces the computer storage requirements by considering at each stage only some initial feasible policy and those states some specified increment above and below. The final policy becomes the initial policy for the next iteration. A number of iterations are necessary, and, generally, the increment is large at first and then refined as the optimization progresses. The number of iterations necessary for reasonable optimization depends strongly on the initial policy chosen. This method is presently used by the Central Valley Project to calculate a monthly policy for their four major storage reservoirs. Typically, a 12-month run on their CDC Cyber-74 computer requires about 7-1/2 minutes. However, to do this well required the development of a separate adaptive algorithm for the computation of initial policies. This method still suffers from problems of dimensionality. The total number of release combinations is easily shown to be 9^N per month where N is the number of reservoirs. It is generally conceded that incremental DP is limited to a 4-reservoir system. Since the CVP is being expanded another solution algorithm is necessary.

The dimensionality problem is reduced still further by the use of incremental dynamic programming plus successive approximations. With this type of decision model an initial feasible policy is still needed and its proximity to the optimal solution will influence the number of iterations needed and thus the computer time. One reservoir at a time is optimized with incremental DP, the others remaining at their constant assigned states. Each reservoir is optimized in turn to complete one cycle or iteration. A number of iterations will be necessary. With this method only 9 release combinations per period need to be considered. TVA is developing this method for their system. Data for a 6 reservoir portion of their system indicates that eight to twenty minutes of IBM 360/50 computer time was needed for a 53-week sequence. TVA has

about 34 major hydro plants so that application to the entire system should take appreciably more time.

A possible problem with this technique is convergence to the optimun. Whereas TVA apparently did not encounter too much of a problem, CVP tried this method unsuccessfully. The technique failed because of a water constraint which forced a release change to occur in one direction only when only one reservoir at a time was considered. This did not improve the objective function and the process stopped. Further optimization required simultaneous release changes in two or more reservoirs.

A mathematical model of a hydropower system can be formulated so that the nonlinearities arising from the power and energy relationships are relatively weak. A major contributor to the nonlinearity is the variable head at the turbines consequent to storage reservoir release. That is, the average head depends on both initial and final storages but the final storage can be calculated only after the release is determined with inflows assumed known. However, if the calculations are decomposed by months or half-months, the storage changes are normally not too radical; changes over a day are usually negligible, at least for the major storage reservoirs. Thus, it might be expected that linearization of the system model might be feasible and the powerful techniques of linear programming (LP) would be applicable for optimization. Linearization by repeated iteration — solving the LP, obtaining the final storage vector, correcting the power relationships, and iterating again — can result in very satisfactory accuracy, provided the nonlinearity is not too severe.

Another aspect of the nonlinearity situation is that in many cases an undue emphasis has been placed on it. The greatest effect (insofar as variable head is concerned) is on the monthly model which can, in any event, only act as a long-term guide. Further, the monthly (and daily) models average out plant-wide generation and do not go to the level of individual unit efficiency curves wherein stronger nonlinearities reside. Firm daily plant release policy should be determined from a daily model, and generated power and energy is fully optimized in accordance with a 24-hour specified power demand profile and the daily plant releases as constraints by an hourly model at the individual unit level. In other words, decomposition of the problem by time

to minimize computational requirements should go hand-in-hand with greater
detail and a minimum of approximation in the shorter period sub-model to
produce accurate calculations. Too much sophistication and complexity for
the longer period sub-models can be wasted.

With this preamble the LP-DP decision models developed for the
monthly and daily release policy determinations for the Central Valley Project
can be described. The monthly model will replace the incremental DP pre-
sently used before two new reservoirs, slated for service before 1980, come
on line. The objective of the technique is to present to the system manager
a set of optimal release policies (and resulting final storage vectors), each
policy corresponding to a different value of total generated hydropower, all
values being greater than contractual requirements. As might be expected,
the most advantageous storage vector for continued operations corresponds
to the lowest value of hydropower. However, each release policy is optimal
in that releases are obtained from each reservoir in each period such that the
best possible final storage vector results for some particular value of hydro-
power generation. Thus, the system manager can select a policy which will
reasonably assure continuing operations and represent efficient management
of the system. It is easily shown that this procedure will minimize reservoir
spilling.

Commencing with the first period, the initial storage states are known
and a linear program with an objective function of minimizing the loss of
potential energy of the stored waters and a constraint set including the contrac-
tual hydropower constraint is applied to determine an optimal release policy.
The hydropower constraint is incremented a specified value and the resulting
release policy starting from initial storage values determined again. This is
repeated until the system cannot respond properly. Consequently, at the end
of the first period, there will be a set of end of period storage vectors cor-
responding to the set of release policies determined for each value of the
hydropower constraint. Starting the second period the whole procedure is
repeated for each end of period storage vector determined for period 1.
Clearly, there will result a much larger set of storage vectors and release
policies and the sets will grow exponentially with the number of periods if
the the process is continued.

Instead, a DP process is inserted between periods to select a best policy path and eliminate most of the possible combinations. The state variable of the DP is the cumulative energy generated, the decision variable is the value of the hydropower constraint in the last period for which solutions have been obtained, and the objective is to maximize the end of period storage vector. (For example, maximize a weighted sum of the vector components.) Thus, at the end of each period, including the final period, there will be an optimal release policy and end of period storage vector for each value of the cumulative energy generated up to that period. The system manager selects the final storage vector he desires along with the consequent release policy and proceeds to the shorter period sub-model.

Although many LP solutions are necessary each solution takes very little time since each LP problem is small (and is made smaller still by the use of dual theory to transpose columns and rows of the constraint set). The complete CVP system over either 12 months in monthly periods or 31 days in daily periods takes approximately 1 minute on an IBM 360/91 computer.

The out of kilter model is another version of linear programming which is very efficient provided that the mathematical model of the system and its constraints can be structured as a transportation or network flow problem. This may not be possible for some systems. The method was tried by TVA for a 53 week time span, all periods being considered simultaneously, and was not too successful. The basic reason seemed to be difficulty in linearization of the model. This is not surprising since over a period of a year the power and energy relationships would be sharply nonlinear.

Some mixed decision models have been proposed but none are known to have been developed to the point of actual or intended use. Essentially, the problem is decomposed in space, or time, or both, and the subproblems solved by DP or incremental DP. A linear program is then utilized to integrate the separate solutions into an overall optimal solution. Repeated iterations are always necessary.

The DP-LP method was first proposed for an analysis of the combined major water resource projects in the Central Valley of California. The system was decomposed in space and the subproblems solved by DP.

Decomposition in time only would, of course, have brought with it the dimensionality problem discussed earlier. Each plant was individually optimized for revenue return from production of firm energy, off-peak energy, and firm water, having been given an intial set of prices for each. Using all of these optimal outputs a linear program optimized the mix of the three decision variables from each of the plants over the total number of time periods. Shadow prices obtained from the dual of this program provide a new list of individual prices for a second iteration of the procedure. Hopefully, the process will converge to a global optimum.

The basic limitation of this method is that all plants must be in parallel since cascaded plants are interdependent in a way which is violated by the space decomposition. This is a severe limitation although the particular application was restricted to parallel plants. Nevertheless, convergence difficulties were encountered and the development was not completed. The difficulties have not been fully explained.

Another proposed model using a similar idea provides for decomposition in space and time with interrelationships treated in a linear Dantzig-Wolfe master program. This master program determines the percentage of each subproblem solution to be used in the overall optimal solution. This method was reported for a three plant system over a three year period in monthly steps. The authors ran into debugging problems and cycling about the extremal points of the master, so that no firm conclusions were reached. Approximately 1/2 hour was required to reach optimality after some changes in the program.

It is not possible to make an objective and conclusive comparison of these various decision models without applying all of them to a number of different hydropower systems. When convergence does occur, all should give approximately the same release policies. The major differences are, as indicated previously, in the applicability, convenience, computational requirements, and requirement for a near optimal initial policy. In these regards, the LP-DP procedure would appear to be more advantageous.

None of the preceding models has been applied to an hourly (or half-hourly) hydropower system optimization on an individual generating unit basis,

although one is being developed for CVP to combine with the monthly and daily models. A successful development and integration into system operations will increase hydropower production over and above any increase resulting from better runoff information.

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APPENDIX D

REVIEW OF REMOTE SENSING
EXPERIMENTS AND APPLICATIONS

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APPENDIX D

REVIEW OF REMOTE SENSING EXPERIMENTS AND APPLICATIONS

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1.   Introduction

This appendix presents a general review and documentation of the current state of the art capabilities of remote sensor systems for watershed modeling and hydrologic forecasting. Emphasis is on hydropower generation. It is the purpose of this review to determine: which remote sensing applications for watershed modeling and hydrologic forecasting are well documented; areas in which major research efforts are being carried forward; gaps in current research; and finally, the specific applicability of the research to hydropower production. Following this introduction we provide an executive summary (Section 2) which documents the goals and methodology of the study, discusses specific hydrologic model parameters and significant remote sensing documents addressing these parameters, and gives the conclusions of our review. Section 3 contains a discussion of current state of the art applications of remote sensing in hydrologic forecasting and watershed management as they relate to hydropower generation. Section 4 presents the conclusions drawn from this assessment.

2.   Executive Summary

Goals

The goals of this task are to assess and document the current state of the art capabilities of remote sensor systems for watershed modeling and hydrologic forecasting; emphasis is on hydropower generation:

- What major research efforts are being carried forward
- Where are the gaps in current research
- What applications are well documented.

Methodology

An identification of major hydrologic models is made and inputs to these models defined. An assessment is made of the degree to which input data for various hydrologic models overlap; model input parameters amenable to remote sensing are extracted and grouped according to a temporal classification:

- Slowly changing
- Moderately changeable
- Dynamic.

Available documents are carefully reviewed, evaluated, abstracted, analyzed and reported on with respect to:

- Goals of the research
- Parameters reported on
- Findings of investigations
- Recommendations.

2.1   Slowly Changing (Stable) Parameters

These are permanent or semipermanent features which change very slowly over a number of years. Despite their slowly changing character, relative variations in given parameters can cause major variations in between-basin runoff characteristics. The parameters include:

PCTIM   —   the permanently impervious fraction of the basin contiguous with stream channels.

AREA   —   area of watershed in square miles

OFSS   —   average slope of the overland flow surface

OFSL   —   average overland flow surface length

OFMN*   —   Manning's roughness coefficient for overland flow on pervious surfaces

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*Mannings's coefficients are derived from landcover data which tend to change relatively slowly in upland catchment basins.

OFMNIS[*] — Mannings's roughness coefficient for overland flow over impervious surfaces

Remote sensing can play a role with respect to the identification and delineation of these parameters. All are obtainable from aerial photography; LANDSAT D is satisfactory for:

PCTIM

OFSS

OFMN

OFMNIS.

Low frequency coverage is required, therefore, little systems cost-benefit leverage is available.

2.2 Moderately Changeable Parameters

These are parameters which change on a monthly or seasonal basis. Remote sensing can play an important role in the detection, identification and delineation of these parameters, however, the frequency of observation of this class of parameter offers limited cost-benefit potential for remote sensing techniques. The parameters include:

ADIMP — fraction of the basin which becomes impervious as all tension water requirements are met

SARVA — fraction of the basin covered by streams, lakes and riparian vegetation under normal circumstances

UZTWM — the depth of water which must be filled over non-impervious areas before any water becomes available for free water storage

VINTMR — vegetative interception maximum rate

RAWT — precipitation data station weights

SIAC — seasonal infiltration adjustment constant (frozen areas and temperature effects)

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[*]Manning's coefficients are derived from landcover data which tend to change relatively slowly in upland catchment basins.

(WES)[*] — water equivalent of snowpack for complete areal coverage

(FCI)[*] — forest-cover index (and other land cover, i.e, agriculture, urban rangeland)

(AESC)[*] — areal extent of snow cover.

LANDSAT D can provide ADIMP, SARVA and VINTMR almost unaided, and can significantly assist in obtaining (AESC). LANDSAT D can also help extrapolate UZTWM from sampled-collateral data. Measurements of (WES), SIAC, and RAWT will require an appropriate mix of SMS, other METSATS, DCS and special HYDROSATS.

2.3   Rapidly Changing (Dynamic) Parameters

These parameters typically change on a weekly, daily, hourly or more frequent basis, and offer potentially large cost-benefit leverage for monitoring by remote sensing. The parameters include:

UCTWC — initial moisture condition of upper zone tension water

PCTPN — daily evapotranspiration index (ETI)

(RMP)[*] — radiation melt parameter

(IDNS)[*] — index density of new snow

(DGM)[*] — daily ground melt

(DMMT)[*] — daily maximum and minimum temperatures.

These parameters and improved forecasting present major opportunities for application of remote sensing. However, residual benefits from Anderson and improved Anderson (NOAA) snow melt models may be less than hoped for. Complex mixes of meteorological and other satellite data will be required. A potential for determination of areas and amounts of actual precipitation exists and may be included by proper modification of the hydrologic

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[*]Parens enclose non-standard acronyms.

models. Optimum systems development requires inclusion of improved forecasts of meteorological events into the model:

- Precipitation forecasts
- Temperature forecasts
- Net radiation forecasts.

2.4   Overall Conclusions

Major conclusions which can be drawn from this survey include:

- Limited work concerning the applications of remote sensing to hydrologic forecasting for hydropower management has been accomplished.

- Other than work by Salomonson, Rango, IBM and Blanchard, little research on remote sensing inputs to hydrologic models has been completed.

- Major research is underway on:
  - Areal extent of snow cover
  - Forest cover index (and other land cover)
  - SARVA (fraction of stream covered by streams, lakes and Riparian vegetation)
  - UZTWC (initial moisture conditions of upper zone tension water.

- Remote sensing can provide significant data on 21 watershed model parameters of importance to hydropower systems managers:
  - 6 slowly changing
  - 9 moderately changing
  - 6 rapidly changing.

  The latter are the most critical to the efficient operation of reservoir management.

- No research thoroughly documents the required mix of:

  — Sensor platforms

  — Sensor systems

  — Spatial and temporal resolutions

  — Sensitivities

  — Recording and receiving station capabilities

  — Data dissemination systems

  — Data Collection Systems (DCS)

  — Collateral Data

  — New models to provide hydropower systems management personnel with the information required to upgrade their decision making.

3.   Discussion of Specific Hydrologic Model Parameters

3.1   Objective

This section gives a synopsis of remote sensing literature as it pertains to hydrologic models in general, and to specific watershed model parameters in particular.

3.2   Approach

An analysis of a number of watershed models was made in conjunction with the activities reported in Chapter 5. Model inputs to the SSAR, Generalized Streamflow Simulation System (GSSS), Stanford Watershed Model IV, and the Kentucky Watershed Model were defined. These were evaluated in terms of the potential for measurement of the various model input parameters by remote sensing. A matrix was then developed giving the model inputs and the degree to which they were amenable to remote sensing (see Table D-1). The sensing of each parameter for each wavelength was ranked on a scale from zero to three: 0 (blank) indicates an insignificant contribution (future application potential insignificant); 3 (three) is a substantial contribution with no additional verification required. As with all matrices this one has shortcomings. It does not, for example, indicate that an optimum solution in gathering

Table D-1. Tentative Hydrologic Model Inputs Amenable to Remote Sensing. (1 of 2)

	Ultraviolet .28 µm – .38 µm	Visible (Photographic) .38 µm – 1.1 µm	Thermal Infrared 3.5 µ – 14 µ	Passive Microwave 1 mm – 3 mm	Active Microwave 1 mm – 3 cm
PCTIM* — the permanently impervious fraction of the basin contiguous with stream channels		3	1	1	1
ADIMP — fraction of the basin which becomes impervious as all tension water requirements are met		2	2	2	2
SARVA — fraction of the basin covered by streams, lakes, and riparian vegetation under normal circumstances		3	2	2	2
UZTWM — the depth of water which must be filled over non-impervious areas before any water becomes available for free water storage			1/2	1/2	1
RAWT — precipitation data station weights		1/2	1	1	1
UZTWC — initial moisture condition of upper zone tension water		1	2	2	1
PCTPN — daily evapotranspiration index (ETI)		2	2	2	1
AREA** — area of watershed in square miles		3	2	2	3
VINTMR — vegetative interception maximum rate		2	1	1	1
OFSS — average slope of the overland flow surface		3			2
OFSL — average overland flow surface length		3			2

	Ultraviolet .28 µm - .38 µm	Visible (Photographic) .38 µm - 1.1 µm	Thermal Infrared 3.5µ - 14µ	Passive Microwave 1 mm - 3 mm	Active Microwave 1 mm - 3 cm
OFMN — Manning's roughness coefficient for overland flow on soil surfaces		2	1	1	2
OFMNIS — Manning's roughness coefficient for overland flow over impervious surfaces		2	1	1	2
SIAC — seasonal infiltration adjustment constant (look at frozen land and temperature effects)		1/2	2	1/2	1/2
radiation melt parameter			2	1/2	
water equivalent of snowpack for complete areal coverage			1	1	1
index density of new snow				1	1
daily ground melt			1	1/2	?
daily maximum and minimum temperatures			2	1	
forest cover index (and other land cover, i.e., agriculture, urban, rangeland)		3	2	2	2

Blank = contribution insignificant. (Future application potential insignificant.)
  1 = contribution not demonstrated but promising for future applications.
  2 = contribution significant but requires additional verification.
  3 = contribution substantial: requires no additional verification.
  *Parameters from the GSSS Model.
  **Parameters from the Kentucky Watershed Model.

information on an input parameter may be found in some combination of multiband, multispectral, multitemporal, or multistage approaches.

In order to explore these model parameters more closely, subdivision of the parameters is required with respect to frequency of environmental change. The model parameters of Table D-1 were therefore subdivided into three categories according to the rate at which parameter characteristics change. The three categories were: 1) slowly changeable, or essentially stable permanent or semi-permanent parameters such as topographic, geologic and soil features; 2) moderately changeable parameters which change seasonally or monthly, such as degree of ground cover, and areal extent of snow cover, and 3) rapidly changeable or dynamic parameters which change weekly, daily, or hourly. The results of this categorization of the model input parameters are shown in Table D-2.

A review of the remote sensing literature was next initiated. Since the field is moving rapidly, special emphasis was placed on papers presented at recent symposia. The most valuable were the Tenth International Symposium on Remote Sensing of Environmental (Michigan, April 1975, the Earth Resources Survey Symposium (Houston, June 1975), and the Workshop on Operational Applications of Satellite Snowcover Observations (Tahoe, August 1975). Each article was analyzed as to: 1) the objectives of the research, 2) watershed parameters covered, 3) sensor systems, and, 4) significant conclusions or recommendations reached. In presenting this material, the discussion follows the earlier subdivision of parameters based on their rapidity of change: slowly, moderately, and rapidly changing. However, before summarizing this material, a number of general studies of wide applicability are examined.

3.3   Discussion of General Studies of Wide Applicability

Three papers by Rango (1975), Salomonson, Ambaruch, Rango, and Ormsby (1975), and Salomonson, Ambaruch and Simmons (1975) are of general applicability.

Rango's paper examines the general potential of remote sensing for watershed management (Rango, 1975). He discusses roles for high altitude aerial photography, LANDSAT data, and SKYLAB and NOAA satellites as

Table D-2. Temporal Classification of Watershed Model Parameters.

Slowly Changing (Stable)	Moderately Changing	Dynamic (Rapidly Changing)
PCTIM** — the permanently impervious fraction of the basin contiguous with stream channels	ADIMP — fraction of the basin which becomes impervious as all tension water requirements are met	UZTWC — initial moisture condition of upper zone tension water
AREA*** — area of watershed in square miles	SARVA — fraction of the basin covered by streams, lakes, and riparian vegetation under normal circumstances	PCTPN — daily evapotranspiration index (ETI) — radiation melt parameter
OFSS — average slope of the overland flow surface		— index density of new snow
OFSL — average overland flow surface length	UZTWM — the depth of water which must be filled over non-impervious areas before any water becomes available for free water storage	— daily ground melt — daily maximum and minimum temperatures
OFMN — Manning's roughness coefficient for overland flow on pervious surfaces	RAWT — precipitation data station weights	— areal extent of snow cover*
	VINTMR — vegetation interception maximum rate	
OFMNIS — Manning's roughness coefficient for overland flow over impervious surfaces	SIAC — seasonal infiltration adjustment constant (look at frozen land and temperature effects)	
	— water equivalent of snowpack for complete areal coverage	
	— forest cover index (and other land cover, i.e., agriculture, urban, rangeland)	

*This parameter can be considered moderately to rapidly changing.

**Parameters from the GSSS model.

***Parameters from the Kentucky Watershed Model.

well as future systems. Among the parameters examined is watershed impervious area, noting that this parameter consists of a combination of specific land uses. The extraction of an integrated percent-of-impervious-area parameter would be exceptionally useful and has been investigated in the Anacostia River watershed in Maryland by Ragan (unpublished results, 1975). LANDSAT automatic classifications of impervious area were compared to results from an earlier study which employed manual measurements taken from low altitude, large scale aerial photographs. Approximately 94 man days were required to complete the required land use analysis using the aerial photographs. Less than three man days were required to accomplish similar tasks using the LANDSAT data. Analysis of the LANDSAT data provided an estimate of basin imperviousness of 19% whereas the aerial photographic study resulted in a 24% figure. Agreement between the conventional photographic method and the LANDSAT approach was excellent for subwatershed areas as small as 1.48 sq km. Ragan (unpublished results, 1975) felt that the correspondence between the two methods was more than adequate for any of the hydrologic model input requirements.

A sensitivity analysis of the Kentucky Watershed Model was also performed to identify input parameters amenable to remote sensing. He concluded that input parameters obtainable with remote sensing at an acceptable accuracy include 1) watershed area, 2) fraction of impervious area (FIMP), 3) water surface fraction of the basin (SARVA), 4) vegetation interception maximum rate (VINTMR), 5) mean overland flow surface length (OFSL), 6) overland flow roughness coefficient (OFMN and OFMNIS), and 7) fraction of the watershed in forest (Forest Cover Index). Other parameters were identified that can be obtained either through improvements in image interpretation or through new remote sensing methods. Tests are also underway to see if remote sensing-based model calibration provides better streamflow simulations than calibrations using conventional data. Numerous models, watersheds and kinds of remote sensing data are being examined.

With respect to LANDSAT's ability to provide information on SARVA, Forest Cover Index, and Area, respectively, Rango states:

- Surface water features as small as 0.01 sq km can be measured.

- Knowledge of watershed land use is important. It is generally agreed that valuable land use maps can be produced from LANDSAT data at scales of 1:62,500 and 1:24,000.

- Research by Rango, Foster, and Salomonson (1975) indicates that watershed area, watershed shape, and channel sinuosity measurements from LANDSAT are generally comparable to similar physiographic measurements derived from topographic maps regardless of the study area.

Rango concludes by stating that today's aircraft and satellite remote sensing systems (operational and experimental) are capable of contributing greatly to watershed management, primarily in the areas of snow mapping, surface water inventories, flood management, hydrologic land use monitoring, and watershed modeling. These remarks are tempered, however, with the statement that while:

"Much of the information capable of being extracted with remote sensing approaches mentioned in this paper can be used in the calibration or operation of numerical watershed models, especially in data sparse regions ... the question that must be answered is whether the necessary data can be extracted with remote sensing at the appropriate scale or accuracy."

In addition to these items, Rango also writes about research on soil moisture and snow cover, both important watershed model parameters. With respect to soil moisture (which relates to UZTWC; see Table D-1), Rango states:

"Soil moisture is one of the most important parameters needed for solving water balance equations for watersheds ... remote sensing techniques for assessing soil moisture are currently being developed and have yet to be fully tested."

Of the five parameters listed as presenting a challenge to space technology the authors note that:

"The measurements of albedo or fraction of incident radiation reflected (FIRR) bears some relationship to PCTPN and radiation multiparameters. For example, using bidirectional reflectance measurements from satellites will require development of sufficiently accurate reflectance to albedo relationships and the proper consideration of the anisotropic nature of the reflected solar radiance. In addition, remotely-sensed measurements of soil moisture over depths corresponding to the root zone (or the "A horizon" in soils) that are accurate to ±7% remain to be accomplished using remote sensing. However, over bare, smooth fields where the soil type is known, microwave measurements appear to hold substantial promise. Here the passive microwave measurements appear to provide accuracies in the ±5% range in the upper few centimeters of the soil. If it can be shown that these measurements can be extended via improved interpretation to greater depths and conditions or a technology is developed for directly measuring lower layer soil moisture while retaining ±7% accuracies, the goal specified for LZC related to both UZTWC and ADIMP by this study will have been reached. Finally, in the case of precipitation and evaporation (RAWT and PCTPN) no direct means of measuring these parameters from space exists. However, it may be that useful empirical relationships can be developed so as to infer precipitation using meteorological satellite observations of cloud type, reflectance, or cloud top temperature. Most recently, use of geosynchronous satellite data such as that from SMS-1 and SMS-2 appears to be the most promising."

The authors also conclude that the use of watershed models and sensitivity analysis is a valuable means of exploring the achievements necessary for using remote sensing as a tool in water resources management. Additional studies of this kind should be made and checked with carefully planned observations.

In an article which follows the same general lines, Salomonson, Ambaruch, and Simmons (1975) examined 46 watershed model input parameters

In regard to snow cover mapping he notes:

- The most definite parameter related to snowpack that can be extracted from aircraft or spacecraft data is the area of the watershed covered by snow.

- Analysis of several watersheds using simple regression techniques shows that a relationship exists between area of snowpack and run-off that is significant at the 99% level.

The research by Salomonson, Ambaruch, Rango, and Ormsby (1975), used a continuous simulation watershed model to perform sensitivity analyses. These then provided guidance in defining remote sensing requirements for the monitoring of significant features and processes. By fixing the permissible variation or specification of the output variable, the problem was inverted such that acceptable tolerances could be specified for input parameters to be measured by remote sensing.

Of 26 input parameters having meaningful effects on simulated runoff, six appeared to be obtainable by existing remote sensing techniques, including satellite borne sensor. These six are: FIMP (PCTIM), FWTR (SARVA), FFOR (Forest Cover Index), OFSL, VINTMR, and OFMN. They noted, how-ever, that the results must be used judiciously because there are several aspects that must be examined further in defining remote sensing requirements for watersheds. First the simulation was carried out for three different water-sheds with a one-year data base containing representative storms in each of four seasons. This set of simulations should be broadened to include other situations and/or environments. Furthermore, the parameters were varied one at a time to ascertain the effects on runoff. In actuality, several would vary together and hence remote sensing requirements would be more stringent than indicated.

In addition to the six parameters listed above, five other parameters were reported as presenting significant challenges to space technology if "one uses the specifications provided by the sensitivity analysis." The 15 remaining parameters were eliminated because in the author's assessment they were either not measurable with remote sensing techniques or were of low sensitivity.

of which 20 were found to have no meaningful effect on the simulation accuracy of the basins modeled. The remaining 26 were analyzed to quantify their permissible tolerances as a basis for estimating remote sensing resolution requirements. The basic objective was to determine acceptable accuracies for remotely sensed measurements used as inputs to hydrologic models of watersheds for streamflow synthesis.

The study objective was achieved by performing a series of sensitivity analyses, using continuous simulation models of three watersheds, to determine the following: 1) the optimal values and permissible tolerances of inputs to the model needed to achieve an acceptably accurate simulation of streamflow, 2) model inputs that can be quantified from remote sensing, directly, indirectly, or by inference, and 3) how accuracy requirements for remotely sensed measurements (from spacecraft or aircraft) used in streamflow models.

The principal conclusions were:

- It is feasible to measure eight of the model inputs from SKYLAB and LANDSAT-1 bulk-processed images:

  - FIMP (PCTIM)   Impervious fraction of basin area

  - FWTR (SARVA)   Water surface fraction of basin
                                 area

  - VINTMR   Vegetation interception maximum
                                 rate

  - ETLF (related to PCTPN)   Evapotranspiration loss factor

  - OFSL   Mean overland flow surface length

  - OFMN   Overland flow surface roughness
                                 coefficient

  - FFOR (Forest Cover Index)   Fraction of watershed in forest

  - FFSI   Fraction of snow intercepted.

- Ongoing research and development in sensor technology and image data analysis indicate a strong near-future potential for quantifying

seven additional model inputs from image data comparable to that of SKYLAB AND LANDSAT-1. These are:

— BUZC   Upper zone storage capacity*

— SUZC   Upper zone capacity seasonal adjustment factor*

— LZC   Lower zone storage capacity*

— BMIR   Base maximum infiltration rate*

— OFSS   Mean overland surface

— ELDIF   Elevation difference between base thermometer and mean basin elevation

— FFIR   Fraction of incoming radiation reflected by snow.

- Other inputs listed in the report were found to have sufficient influence on simulation accuracy to be of interest, although they are only practicably measurable by ground survey or low-flying aircraft or by calibration based on historical observations. All of them are potential candidate measurements for future data collection systems using satellite relay, and permissible tolerances have been estimated as a basis for accuracy requirements on such future systems.

In addition to these parameters Salomonson, Ambaruch, and Simmons (1975) also discuss the potential for the determination of 1) snow parameters and, 2) soil moisture, as well as the possibility for future direct measurements of 3) evapotranspiration and, 4) precipitation by field instrumentation and satellite relays. While they reach no specific conclusions nor give recommendations concerning the future role of remote sensing to hydrologic modeling, the evidence they present indicates that they feel remote sensing can play an important role in hydrologic modeling.

These broad studies along with those of Burgy, Storm, Horton, and Malingreau (1972), Burgy, et al., (1973), IBM (1973), and Salomonson (1974), set the tone for the following sections of this report. These broad analyses show the general applicability of remote sensing to hydrologic modeling.

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*Note: The author presumes these parameters can be inferred from land use analyses.

3.4   Slowly Changing (Stable) Hydrologic Model Input Parameters .

Stable model parameters which are amenable to remote sensing
include:

PCTIM   — the permanently impervious fraction of the basin
           contiguous with stream channels

AREA   — area of watershed in square miles   .

OFSS   — average slope of the overland flow surface

OFSL   — average overland flow surface length

OFMN   — Manning's roughness coefficient for overland flow
           on previous surfaces

OFMNIS   — Manning's roughness coefficient for overland flow
           over impervious surfaces.

3.4.1 PCTIM — The Permanently Impervious Fraction of the Basin, Contiguous with Stream Channels

There are numerous studies using remote sensing to obtain data on
model parameter PCTIM (the permanently impervious fraction of a watershed
which is contiguous with stream channels). Burgy, et al., (1973) state that
PCTIM is currently derived from "hydrographic analysis (i.e., based on an
analysis of the characteristics of flow volume past a gaging station with
respect to time)." However, IBM in discussing FIMP (impervious surface
fraction) — a watershed parameter from a model not considered in this study,
but closely related to PCTIM — notes that it is "usually estimated from aerial
photography". (IBM, 1973) Photo interpretation of bare rock surfaces, by
lithologic type, is commonplace (Howard, 1970; Colwell, 1960; Avery, 1968;
Miller, 1961; von Bandt, 1962). Recent work using principally LANDSAT
imagery and digital tapes for the same purpose is reported by Rango (1975),
Salomonson, Ambaruch, Rango and Ormsby (1975), Salomonson, Ambaruch
and Simmons (1975), Jackson (1975), Jackson, Ragan, and McCuen (1975),
and Houston and Marrs (1974).

The works of Jackson (1975) and Jackson, Ragan and McCuen (1975)
dealing with the determination of percent impervious area within urban water-
sheds are particularly relevant. These papers show the types of machine

processing that are of value in delineating areas of bare rock. They found that LANDSAT data can provide estimates of acceptable accuracy for urban hydrologic planning models and some design models.

Finally, with respect to PCTIM a study with SKYLAB data (Houston and Marrs, 1974) in Wyoming on general geologic, tectonic, land use and vegetation mapping provide additional clear indications of the capability to map impervious surfaces from space photography.

3.4.2 AREA (Area of the Watershed in Square Miles)

Area is defined as the area of a given watershed in square miles. With respect to measurement of area recent works by Rango, Foster and Salomonson (1975), Salomonson (1974), and McCoy (1967) complement standard general books such as Avery (1968), Colwell (1960), and Howard (1970) which deal with area measurements on aerial photography. Rango, Foster, and Salomonson used LANDSAT data at scales of 1:250,000 and 1:100,000 of areas in Southwestern Wisconsin, Eastern Colorado and portions of the Middle Atlantic States and found that measurements of drainage basin area, shape and stream sinuosity were comparable (within 10%) in all study areas to physiographic measurements derived from conventional topographic maps at the same scales. They concluded that "ERTS-1 imagery can be employed to advantage in mean annual runoff prediction techniques and in providing or maintaining land use information used in the calibration and operation of watershed models."

McCoy (1967) examined how well active microwave systems might provide drainage basin information. He analyzed drainage basins as seen on a Ka-band radar imaging system, determined means of converting radar image terrain data to a topographic map equivalent, examined the extent to which radar images can be analyzed using standard geomorphic techniques, and studied procedures for automatic measurement of drainage basin parameters. The result of McCoy's analysis indicate that drainage area, basin perimeter, bifurcation ratio, average length ratio and cirularity ratio can be measured from the imagery with little variation from map-derived values. McCoy goes on to conclude that:

"The use of radar imagery in hydrology will be for measurement and analysis of those terrain parameters which influence the hydrologic

cycle. With the large quantity of data contained on radar images, it will be possible to use radar as a substitute for maps to obtain additional terrain parameters relating to runoff, and thereby develop somewhat greater precision in prediction of streamflow."

Salomonson (1974), in his summary of Significant Results for Water Resources at the Third Earth Resources Technology Satellite Symposium states that:

"Digital data and computer techniques have been used to delineate watershed features in Colorado, and in particular it was found to be possible to obtain drainage basin area to within two percent of that obtained from other reliable and conventional data sources. Results have also been reported from the Oklahoma area concerning the use of ERTS data for estimating coefficients in runoff equations that are used to design small flood-control structures. These equations are the type that are usually referred to as the 'rational' formula equations, where the discharge is a function of the area of the watershed, the intensity of precipitation, and a coefficient, which takes into account the forest cover, slope, and the general character of the watershed."

3.4.3 OFSS (Average Slope of the Overland Flow Surface)

The average slope of the overland flow surface (OFSS) is generally determined in association with OFSL (overland flow surface length) discussed in Section 3.4.4. For convenience, the same points selected for OFSL may be used to determine OFSS. From each point selected, the height differential from that point to the nearest watercourse can be determined by counting the contour lines and multiplying by the contour scale. Since the length of the overland flow surface at that point was measured when determining OFSL, OFSS is then equal to the change in height (Δh) divided by the average of the local OFSS values.

As noted by Salomonson, Ambaruch, Rango and Ormsby (1975), this parameter (OFSS) can be obtained from either stereo photography or radar altimetry. Indeed, Salomonson, Ambaruch and Simmons (1975) state that knowledge of basin topography is necessary for the derivation of the mean

overland surface slope and that such information is "readily measured from stereo image pairs, something obtained from aerial photography, but not at present from space." These authors go on to state that an attractive alternate technique would be to obtain basin topographic data from the output of a spaceborne laser altimeter. It is evident, then, from these works, and the works of: Colwell (1960); Wolf (1974); Thompson (1966); and Spurr (1960) that slope information can more than adequately be derived from stereo aerial photography. It may also be possible to obtain slope information from altimetry. An additional possibility for determining slope from remotely sensed data suggested by McCoy (1967) is the use of active microwave imagery for measuring slope information.

3.4.4   OFSL (Average Overland Flow Surface Length)

Research indicates that the derivation of this parameter from remotely sensed data can be accomplished adequately. Rango (1975); Salomonson, Ambaruch, Rango and Ormsby (1975); Salomonson, Ambaruch and Simmons (1975) all list this as a parameter which can be currently obtained from analysis of a remotely sensed data. Salomonson, Ambaruch, Rango and Ormsby (1975) state that this parameter can be derived from high altitude aerial photography or from data taken by SKYLAB's Earth Terrain Camera. In addition to these works those of Dalke and McCoy (1966); McCoy (1967); Estes and Simonett (1975) with radar and Colwell (1960); Avery (1968); Wolf (1975); Spurr (1960) with aerial photography attest to the capability of remote sensing to supply data relative to this parameter.

3.4.5   OFMN (Manning's Roughness Coefficient for Overland Flow on
          Pervious Surfaces)

OFMN is a roughness coefficient for overland flow derived from published tables dependent on estimated vegetative cover and soil usage. Weighted averages are used where different types of cover are in evidence. The ability of remote sensor systems to provide data relative to this parameter basically rest with the capability of such systems to provide surface cover or land cover information. This ability has been well documented in the works of Avery (1968), Colwell (1960), Wolf (1974), Estes and Senger (1974), Howard (1970) and Holter (1970). Salomonson, Ambaruch, Rango and Ormsby (1975)

list this as a parameter which can be obtained using existing remote sensing techniques. They even state that some categories are applicable with LANDSAT and that high altitude aircraft data are capable of meeting watershed model input data requirements. This sentiment is echoed in the works of Rango (1975) and Salomonson, Ambaruch and Simmons (1975).

3.4.6 OFMNIS (Manning's Roughness Coefficient for Overland Flow Over Impervious Surfaces)

Basically the derivations of OFMNIS is the same for OFMN but applies to impervious surfaces. Although not directly listed as such in the works of Rango (1975), Salomonson, Ambaruch, Rango and Ormsby (1975), or Salomonson, Ambaruch and Simmons (1975) the method of derivation of this parameter makes it highly likely that it can be accomplished in the same fashion as the previous parameter (OFMN). Indeed the works of Jackson, Ragan and McCuen (1975) previously discussed under PCTIM, and Tinney, Jensen and Estes (1975) indicate that for urban areas information concerning impervious surfaces can be derived automatically with relatively high accuracy from remotely sensed data. This along with the documentation already discussed under PCTIM make it evident that remotely sensed data can be used to provide watershed model input data relative to this parameter.

3.5 Moderately Changing Hydrologic Model Input Parameters

For the purposes of this study moderately changing input parameters have been defined as those environmental components which exhibit a seasonal or monthly pattern of change. Those which appear to be amenable to remote sensing include the following items (see also Table D-2):

3.5.1 ADIMP - The Fraction of a Watershed which Becomes Impervious as All Tension Water Requirements Are Met

This parameter is not specifically addressed nor is it discussed in detail in any of the publications reviewed. The two papers by Burgy, et al., (1973) and Burgy, Storm, Horton, and Malingreau (1972) are included here because they allude to the potential of remote sensing to supply data relative to soil type, water content, and infiltration rates. From an analysis of

information concerning these parameters the authors of this document believe that a potential for a reasonable estimate of ADIMP exists.

3.5.2   SARVA - The Fraction of the Basin Covered by Streams, Lakes, and
         Riparian Vegetation Under Normal Circumstances

IBM (1973) states that this "value is estimated from aerial photos and is virtually zero for watersheds containing neither lakes or swamps." There is much material in the remote sensing literature which relates to this parameter. This is also again one of the parameters listed as potentially amenable to remote sensing by Rango (1975), Salomonson, Ambaruch and Simmons (1975), and Salomonson, Ambaruch, Rango and Ormsby (1975). Depending upon the resolution requirements of a particular model this parameter could be obtained from a range of platforms and sensor systems. These range from standard metric cameras in aircraft (e.g., ERB 1973; Coker, Higer, Rogers, Shah, Reed and Walker, N.D.; Kritikos, Sahai, and Trondel, 1974; Holter, Luther and Thorne, 1973), to active and passive microwave and other sensing systems (e.g., Microwave Workshop Report, 1975; Estes and Simonett, 1975; Estes, Brunelle, Hardoin and Lytle, 1975). Indeed Burgy, et al., (1973) state that the estimation for the fraction of the basin covered by streams, lakes and riparian vegetation (SARVA) could begin immediately utilizing a combination of LANDSAT, and supporting aircraft and ground data employed in a proper sampling design.

3.5.3   UZTWM - The Depth of Water which must be Filled over Non-
         Impervious Areas before Water Becomes Available for Free
         Water Storage

The literature reviewed does not specifically address this parameter. However, since UZTWM in essence is a function of the soil type and depth, any contributions of remote sensing must be by inference, and extrapolation from ground observations. There is no doubt that improvements can be made using standard qualitative photo-interpretation procedures with a variety of aerial and space photographic and other sensors. Most mountainous water-sheds are not adequately mapped as to soil type and depth.

3.5.4 RAWT – Weights Applied to Station Rainfall Values to Determine, Basin Mean Rainfall

According to Burgy, et al, 1973, the weights are set according to relative area closest to a given meteorological station and by the rainfall amount for a given station. The resulting basin weight for a given station is then established by optimization with respect to a given mean square error function of a fitting function. Rainfall, or more accurately, total precipitation, amounts for a given meteorological station are determined daily from historical records for model tuning. For a real-time situation, i.e., an application of the tuned model, precipitation amounts may be taken from automatic ground meteorological station readouts, or from phoned-in rain gauge measurements. Precipitation amounts for future periods are estimated from quantitative precipitation forecasts made by meteorologists. These forecasts are derived with standard weather forecasting data and are specific to given reference locations. The resulting data are transformed by a predetermined algorithm to basin precipitation recording stations of interest. Few publications relating to this topic were found in the current remote sensing literature. Nevertheless, certain material indicates that a significant potential for remote sensing of this parameter exists. Specifically the work of Amarocho (1975) using meteorological satellite data to determine: 1) in relation to evapotranspiration computations, 2) identification of days with possibility of rain over specific areas by recognition of cloud types, 3) estimation of precipitation through cloud brightness assessment under cumuliform clouds by verification with ground catch data, 4) use or precipitation estimates obtained as inputs to a mathematical model for a catchment and quantitative reconstruction and verification of streamflows and water balances, shows the potential for providing information relative to this parameter. From personal communication with Amarocho and Earl S. Merritt of Earth Satellite Corporation concerning their work, both felt that the potential to use meteorological satellite data to model and monitor precipitation exists now for cumuliform precipitation. The future potential of this type of study for upgrading hydrologic modeling data is such that it warrants significant future consideration. Salomonson (1974) in his outlook for space in the year 2000 however makes the comment that complex, active microwave systems with range-gating

capability involving synthetic aperture or large antennae on spacecraft appear necessary before precipitation over land can be observed from space. Cooper and Herowitz (1975), among others, discuss the potential DCS/DCP system to relay data relating to this parameter. Burgy, Storm, Horton and Malingreau (1972) indicate that the potential exists for the measurement of precipitation both as rainfall and snowfall for hydrologic research as runoff and flood prediction in the active microwave region (1.0-4.0 cm). In addition, Burgy, et al, (1973) in discussing avenues of investigation for possible remote sensing applications in river forecasting and hydrologic modeling, list as intermediate and long term potentials the estimation of mean total precipitation amount by specified areas (total basin or sub-basin) through the application of meteorological satellite data applied in concert with real-time ground station data (radar, automatic basin meteorological stations) using appropriate sample design, and hard and software integration. From both personal communication and our initial survey of the literature the authors of this report feel this to be an area for significant future use of remote sensing.

3.5.5 VINTMR - Vegetation Maximum Interception Rate

IBM (1973) states that: VINTMR is the maximum rate of rainfall interception by the watershed vegetation expressed in inches per hour. Publications reviewed herein represent only a small portion of the remote sensing literature dealing with the mapping of vegetation. In addition to the general articles by Rango, Salomonson, Ambaruch and Simmons (1975) and Salomonson, Ambaruch, Rango and Ormsby (1975), Burgy, Storm, Horton and Malingreau (1972) note that information on this parameter can be obtained from aerial surveys using sensors operating in the reflective and infrared (0.3 μm to 14 μm) range. Landley (1968) has documented the use of multistage sampling for the detailed mapping of vegetation, while work such as those by Morain (1974), Holter (1970), Estes and Simonett (1975), Rouse, Schell, Deering and Harlan (1974), and Howard (1970) document the capability to extract information concerning this parameter from standard photography, "unconventional" imaging systems and the use of automated interpretation of multispectral imagery.

3.5.6 SIAC - Seasonal Infiltration Adjustment Constant

This parameter is normally derived through optimization, and reflects the mean seasonal differences in soil water contained in the upper soil layers. If, as appears likely, synchronous and orbiting meteorological and hydrological satellites allied with a fine net of Data Collection Platforms are able to provide a continuous estimate of the surficial contained soil moisture, the necessity for deriving a seasonal adjustment factor will be eliminated. There is no doubt in our mind that initially this parameter may be improved through movement to monthly weights and finally eliminated entirely as our ability to model and directly assess contained soil moisture improves.

3.5.7 Water Equivalent of Snowpack for Complete Areal Coverage

A number of articles have appeared in the literature recently on the potential of remote sensing to provide data on this parameter. Salomonson (1974) in his analysis of Water Resources in Outlook for Space 1980-2000, observes that "there are several indications that snow, moisture and ice thickness may be inferred from passive or active microwave data."

As reported in their recent Catalogue of Snow Research Projects (Corps of Engineers, 1975), A. E. Fritzsche is examining the potential of gamma ray surveys for determining the water content of a given snowpack. The report states that "the use of natural terrestrial gamma radiation to measure water equivalent of snow cover from aircraft has been shown to be feasible by previous work in this research project. Current research and development include: 1) assembling an operational system designed for water equivalent measurements, 2) calibrating this new system, 3) experimentally evaluating gain stabilization techniques, and 4) performing experimental water equivalent surveys in important U.S. watersheds." At the recent Workshop on the Operational Applications of Satellite Snowcover Observations, Bissell (1975) in his article on "Application of Bayesian Decision Theory to Airborne Gamma Snow Measurement" notes concerning his research methodology that "measured values of several variables are incorporated into the calculation of snow water equivalent as measured from an aircraft by snow attenuation of terrestial gamma radiation." Bissell goes on to state that

airborne gamma survey, appears to have its greatest potential in plains areas such as the north-central United States.

In that same Workshop on Satellite Snowcover Observations several other important papers related to the remote detection and measurement of snow water content were presented. Leaf (1975) described a procedure whereby the correlation between: a) satellite derived snow-cover depletion and b) residual snowpack water equivalent, can be used to update computerized residual flow forecasts for the Conejos River in southern Colorado. Leaf goes on to state that a stable correlation between snow-cover depletion and residual water equivalent is independent of precipitation input and can be utilized in combination with direct snowpack measurements through the melt season to revise model estimates of streamflow. In most areas, satellite imagery would provide the primary basis for updating streamflow forecasts so long as the drainage basin is partially snow covered. Streamflow forecasts prior to the onset of snowmelt and during those times when the watershed is completely covered with snow would rely on direct snowpack measurements.

Finally the work of Sharp and Thomas (1975) at the Lake Tahoe Workshop describes how LANDSAT imagery can be cost-effectively employed to augment an operational hydrologic model. Attention is directed toward the estimation of snow water content, a major predictor variable in the volumetric runoff forecasting model presently used by the California Department of Water Resources. A stratified double sampling scheme is supplemented with qualitative and quantitative analyses of existing operations to develop a comparison between the existing and satellite-aided approaches to snow water content estimation. The precision of basin water content estimates could be improved still further by using techniques that increase the correlation of orbital to ground snow water content estimates. Smaller image sample units, more environment-specific snow class interpretations, and automatic processing of satellite digital data are some of the more promising of these techniques.

3.5.8 Forest Cover Index

Forest Cover Index (and other land cover, i.e., agricultural and rangeland categories) is the final parameter examined under the moderately changeable input parameter category. This parameter relates to the ability

to derive land cover information from remotely sensed data. This capability
has more than adequately been demonstrated (Morain, 1974; Draeger, 1968;
Carneggie, 1968; Morain, 1974; Culver and Poulton, 1968; Avery, 1968;
Colwell, 1960; Avery, 1968; Howard, 1970; and Holter, 1970). These biblio-
graphic citations and the others are only a small indication of the literature
on land cover (land use) mapping from remotely sensed data. The capability
to accomplish this task as it directly relates to watershed modeling is
attested to in the works of Rango (1975), Salomonson, Ambaruch and Simmons
(1975), and Salomonson, Ambaruch, Rango and Ormsby (1975) discussed
earlier. In addition, Rango, Foster and Salomonson (1975), in their article
on the extraction and utilization of space acquired physiographic data for
water resource development, state that land use information can be usefully
extracted for watersheds as small as 78 sq km. Along the same lines, Rango,
Shinca and Dallam (1975), found remote sensing data to be an acceptable
method for the rapid periodic inventorying of hydrologic land use changes.
Rango, Shinca and Dallam (1975) also note that floodplain delineation and land
use definition as applied in the Patuxent River Watershed is necessary to
develop watershed simulation models for future applications. Using the models,
a better understanding of watershed runoff characteristics may be achieved.
The method described is not only economical but provides for rapid periodic
inventories of hydrologic land use changes which may effect the runoff
response of the watershed.

Other recent articles such as those by Coker, Higer, Rogers, Shah,
Reed and Walker (N.D.) and McKim, Merry, Cooper, Anderson and Gatto
(1975) discuss the hydrology related land use/land cover mapping potential
presented by SKYLAB data. McKim and his fellow authors state that "the
utility of satellite, high altitude and low altitude aerial imagery is presently
being critically evaluated by the Corps of Engineers. When the application
has been demonstrated and is cost effective, it will be used to update or
augment conventional methods and procedures. Our most significant contri-
bution to date has been to increase confidence limits by more accurately
estimating parameters used in model."

3.5.9 Areal Extent of Snow Cover.

This parameter is not a member of any of the three temporal sub-classifications of parameters. However, owing to the significant attention being given this topic in current remote sensing literature it has been added as an independent item. (It is considered to fall between the moderately changing and dynamic categories.)

This parameter is the most extensively documented as to its significant measurement by remote sensors. Rango (1975) in an overview of the applications systems verification test on snow cover mapping, has stated very emphatically that "the capability of the LANDSAT and NOAA satellites to accurately measure snowcovered areas on various size watersheds has been demonstrated by a number of investigators. Additionally, recent research has shown a highly significant statistical relationship between satellite derived snowcovered area at the beginning of the snowmelt period and seasonal runoff."

An extensive array of papers were presented on this topic at the Tahoe Snow Workshop. Rango (1975) cites among the applications of the data that of short duration runoff forecasting, seasonal runoff forecasts — and "with five years of satellite data as a base, meaningful snowcovered area indices could be used in normal regression approaches to streamflow forecasting." Such applications lead to related ones of reservoir regulation for irrigation and power requirements and flood control.

As further examples of this workshop output, Warshow, Wilson and Kerdor (1975) noted that satellite imagery "holds good potential for improved accuracy of volume forecasts" and critical, daily decision-making inputs. Schneider (1975) observed that "satellite snow maps have been favorably compared with aerial survey data in the past." Rango and Salomonson (1975) summarized that "it appears that resource satellite data will be useful in assisting in the prediction of seasonal streamflow, nonhazardous collection of snow data from restricted-access areas, and in hydrologic modeling of snowmelt runoff."

Significantly, prior to this rather assertive workshop, Barnes and Bowley (1974) prepared their Handbook of Techniques for Satellite Snow Mapping to assist in the planning for the practical demonstration of the

application of satellite data to snow hydrology. Their extensive examples corroborate the value of, and the ability to map snow cover with satellite data.

3.6 · Rapidly Changing (Dynamic) Parameters

Dynamic parameters are those which display significant changes within weekly, daily, hourly or lesser periods and hence require a high frequency sampling interval. Those amenable to remote sensing include (see also Table D-2):

UZTWC — initial moisture condition of upper zone tension water

PCTPN — daily evapotranspiration index (ETI)
— radiation melt parameter
— index density of new snow
— daily ground melt
— daily maximum and minimum temperatures

3.6.1 UZTWC — Initial Moisture Condition of Upper Zone Tension Water

The assumption which has been made here is that soil moisture may be approximately related to UZTWC. Idso, Jackson, and Reginato (1975) reviewed the three general regions of the electromagnetic spectrum, being used in current feasibility studies of remote sensing of soil moisture (visible, thermal and microwave). They correlated albedo values (normalized to remove solar zenith angle effects) in the visible with gravimetrically measured water-content values of soil layers in Avondale loam extending to various depths. They found that:

"For all layers in the upper 2 cm, the results were independent of season and indicated that for the soil studied, normalized albedo was a linear function of the water content of the soil surface."

Eagleman and Ulaby (1975) correlated the moisture content as determined by direct measurements at surface depths of soil with outputs of SKYLAB radiometers operating at 2.1 cm (S193) and 21 cm (S194) and the microwave Scatterometer (S193). Preliminary results showed the following:

"The correlations presented have shown good correspondence between the SKYLAB microwave sensors and moisture content of the soil. The

passive radiometers gave correlations of -0.97 (S194) and -0.86 (S193).
The Scatterometer also responded to moisture levels with a correlation
of 0.67."

Blanchard (1975) in his study of the Chickasha watershed (Oklahoma), noted
in his concluding remarks that:

> "Antenna temperatures for the X band passive microwave radiometer
> have been related to soil moisture contained in the surface 6 inches
> of bare ground. Variation in both soil moisture and the passive micro-
> wave antenna temperature appear to limit the possibility of making
> accurate measurements of soil moisture. Anomalies are present in
> the microwave response that at present cannot be explained, but these
> anomalies are reproducible in repeated flights over the same point."

Reconciliation of his comments with the more positive view of the previous
two citations requires some closer inspection of his data. The resolution
elements for the X and Ka band radiometers were about 50.6 ft by 206 ft for
the 5° view angle. In contrast, the L band view angle was 16°. Blanchard
then notes, "plots of antenna temperature versus soil moisture content
revealed no apparent relationship between the 0- to 12-inch soil moisture and
any of the three bands. Soil moisture in the top 6 inches was related reason-
ably well to the X band antenna temperature . Extreme scatter occurs when
the Ka band temperature is used; therefore, there is little evidence that this
band would be a good index of soil moisture in the surface 6 inches. And
finally this pertinent further evaluation of the X band data: "The X band data
from this study was compared to averaged data representing wet and dry soils
from studies at Texas A&M University. The combined data is in good agree-
ment and encompasses a broader range of soil moisture than this study.
Since the relationship appears to be highly significant, it may be possible that
the difference between X band temperatures of the same soil under wet and
dry conditions may be related to soil moisture storage capacity."

Moore, Ulaby, and Sobti (1975) also evaluated the output of the SKYLAB
S-193 radiometer/scatterometer and concluded that "soil moisture was an
important variable that influenced" its response. Their evaluation used pre-
cipitation histories (from NOAA weather reporting station summaries) to

estimate soil moisture. The rainfall data were gridded, extropolated and interpolated pertinent to each S-193 target point estimation. They observed that:

> "This soil moisture estimate (composite rainfall) can be considered
> as another variable describing the terrain target. Its influence upon
> the microwave response was sought by computing a correlation between
> the radar and radiometer response and the soil moisture. This was
> done for some physiographic and land use categories as identified by
> topographic maps and imagery. A pass over Texas in June 1973, was
> then subjected to an intensive study where the effects of soil perme-
> ability and potential, and, to some extent, cloud cover effects, were
> accounted for. The correlation of the radiometer temperature with
> the composite rainfall was found to be over 0.80 (negative); the cor-
> relation with the backscatter coefficient was lower (approx. 0.61)."

Peck, Larson, Farnsworth and Dietrich (1975) have compared con-current measurements of soil moisture from ground sampling and those of passive microwave and gamma radiation made from an aircraft. The micro-wave measurements were made at 4.99 and 13.4 Ghz (both vertical and hori-zontal polarization); the gamma measurements were made over the 0.05 to 3.0 Mev range. Since the gamma measurements most nearly represented the change in soil moisture between two surveys separated by seven days, it was used as 'ground truth' for comparison purposes with the microwave measurements. The authors observed that:

> "Various computational schemes utilizing the microwave measurements
> were used to estimate the change for soil moisture conditions. These
> differences, based on the microwave technique, were found to be well
> related to the change in soil moisture as indicated by the gamma radia-
> tion. Various comparisons were made for measurements over fields
> with different vegetation cover. Although the good relationships
> obtained were based on somewhat ideal conditions (minimum change
> in vegetative cover, excellent ground fix for aerial surveys, extensive
> ground truth, etc.), they do point to the possible use of microwave
> techniques for areal measurement of soil moisture under selective
> conditions for hydrologic purposes."

The outputs of the Nimbus-3 HRIR-D (.7-1.3 μm) sensor were evaluated by Merritt and Hall (1974). They concluded that:

"Study of the data in conjunction with area-averaged precipitation measurements indicate that large area increases in near infrared reflectivity observed between June and August 1969, were closely related to the development of soil moisture deficits in the Mississippi Valley. Comparison of instantaneous area averages of rainfall for the 24 hours just prior to the satellite observation, with averaged reflectance shows a useful relationship in June but random distributions in July and August. Some reasons for this difference may be found in the generally random cumuliform-type precipitation in July and August in comparison with the more uniform stratiform-type precipitation of June."

3.6.2 PCTPN — Daily Evapotranspiration Index (ETI)

Salomonson (1974) makes the following comments regarding the measurement of ETI:

"Substantial evidence exists that soil moisture and evapotranspiration measurement and improved delineation of precipitation may be obtained by combining conventional, in-situ measurements and satellite measurements in the thermal infrared."

He notes that "evapotranspiration has always been a difficult parameter to measure or estimate. Applying remote sensing appears to be especially difficult although estimating evaporation from open water surfaces or delineating regions of large, moderate, and small potential evaportranspiration may be possible. The fact that aquifers containing groundwater are located well below the surface make this a difficult parameter to observe, but skilled geological interpretation of improved space imagery or, possibly, use of very long wavelength (>1 meter) data may make this possible."

Moore, Horton, Russell and Myers (1975) produced "maps estimating evapotranspiration rates of the agricultural landscape using the S-192 SKYLAB data and were evaluated against estimates as determined from ground measurements. Multispectral analyses were pursued to determine those spectral

regions appropriate for mapping various landscape features associated with soil moisture differences." Wet versus dry fields could be distinguished.

Welsh (1975) reporting on activities of the California Department of Water Resources, cites several satellite studies, one of which was oriented toward evapotranspiration estimates using degree of vegetative ground cover and crop stage of growth as estimated from LANDSAT imagery.

Earlier, Burgy (et al., 1973), in testing avenues of investigation for possible remote sensing applications in a river forecasting hydrologic model, foresaw the following in an intermediate and longrun potential implementation period:

> "Estimation of potential evapotranspiration demand (ED) or of coefficients (PCTPN) to weight existing pan evaporation or evapotranspiration estimates in specified areas; application of ERTS data to define ground cover type and physiological condition in accordance with usual sample design."

3.6.3   Radiation Melt Parameters and Daily Ground Melt

The interaction of these variables and many of the contributory aspects is such that a combined discussion is appropriate here. One exponent of interactive analysis, Outcalt (1974), has performed significant work in applying the energy balance concept as an analytical tool. He points out that "the recognition of the interrelationship between geographic material variations and their expression through the evolution of the surface thermal regime is the key to expanding the information content of imagery." He sees the study of "the thermal regimes of mountain snow and ice bodies as reasonble targets for the application of thermal mapping technology ... the variation of surface radiant temperature spatially and temporally contain information about the structure, composition and thermal state of near surface materials. The radiant surface temperature ... is a product of both surface temperature and emissivity ..."

Chang and Gloerser (1975) have used a microscopic model of a snow field wherein individual particles are considered as microwave scattering centers interacting incoherently. This model has "been used to explain qualitatively the brightness temperature over dry and wet snowfields. The

computational results show that scattering from the individual snow particle is a dominant factor in the measured upwelling brightness temperature for dry snow." In contrast, "for wet snow layers of 50 cm or more, the brightness temperatures approach the physical temperature of the snow melt." Burgy (et al., 1973) reaffirm as avenues of investigation for remote sensing the estimation of real-time cloud cover values and the changes in snow shading in specified areas.

Algazi and Suk (1975) note, in that context, that "much remains to be done to develop the procedure for mapping albedo and temperature fields of the snowpack." One study output showed that on the basis of temperature they could discriminate clouds from snow ... and viewed as significant any such progress on the remote detection of cloud cover over snowfields.

Similarly, Barnes (1975) cited the experiments to determine the amount of additional information on snow that can be obtained from sensor measuring in other than the visible and thermal infrared portions. He noted that a "dramatic decrease in the reflectance of the snow surface in the near-IR portion of the spectrum" leads to potential applications in: (a) distinguishing between dry and melting snow surfaces, and (b) distinguishing snow from clouds.

Seifert, Carlson and Kane (1975) discuss "an near real-time operational application of NOAA satellite enhanced thermal infrared imagery to snow monitoring ... Ground truth comparisons show a thermal accuracy of ±1°C for detection of surface radiative temperatures. As a result many important facets of Spring snowmelt ... can be studied ... eliminating much of the former uncertainty and ambiguity of satellite observations ... Studies have also been done with visible imagery to clearly define the relationship of sun angle to both theoretical and measured brightness. By defining the minimum brightness of snow-covered terrain, it is possible to delineate snow cover as a function of brightness and sun angle."

The initial investigations of Brown and Hannaford (1975) "suggest that adequate data on snow covered area may prove of more value in estimating melt rate and updating forecasts than in the preparation of early season water supply forecasts."

Barnes and Smallwood (1975) note the need for further study of snow reflectance characteristics and conclude that "measurements in the near-infrared spectral region, in combination with visible and thermal infrared measurements have the potential of providing greatly improved information with regard to snow hydrology."

Preliminary results from (in situ) microwave experiments by Linlor, Meier and Smith (1975) give some encouragement that the microwave areas will provide data enabling some discrimination of snow wetness or index density properties.

McMillan and Smith (1975) note that:

"Current research on remote sensing of snowpack parameters, other than of areal extent, is largely centered in the microwave and gamma-ray portions of the electromagnetic spectrum. It appears possible, however, to use measurements in the shortwave region to estimate snowpack density statistically. In situ measurements at the Central Sierra Snow Laboratory and remote observations from the LANDSAT-1 spacecraft show the possibility of estimating average snowpack density with albedo or radiance measurements, respectively.... The results of the in situ study at the Central Sierra Snow Laboratory suggest the application of aircraft-mounted radiometers to obtain albedo data for use in estimating average snowpack density. The results of the LANDSAT study, however, are not as acceptable for immediate use in the Sierra Nevadas. Satellite data may be applicable, though, in the broad flat regions of the Midwest.

"The regression equations presented are empirical relationships. Coefficients may need re-evaluation if they are applied to areas where the snow maturation process is different from that near the American River Basin, California."

In their summary they concluded that:

"Albedo or satellite radiance measurements can be used to estimate average snowpack density by means of a multiple linear equation. The in situ data equation predicted density with a correlation (r^2) of 0.79

and a standard error of 0.027 gm cm^{-3}. The data from LANDSAT-1 were not as significant in a similar equation, possibly because of the large field of view."

3.6.6 Daily Maximum and Minimum Temperatures

A significant amount of the preceding discussion on the radiation melt and the daily ground melt parameters is pertinent here. Some additional comments are, however, in order.

Outcalt (1974) points out that "surface thermal response is not independent of the thermal history of the near surface zone" but is a function of diurnal effects "nested within" annual effects. He aptly integrates temporal, spatial and spectral operators (or processing algorithms) to prepare smoothed maps of thermal range.

3.7   Other References

In addition to the works listed above the authors of this appendix feel that a number of other papers from the literature should be mentioned briefly here (see Table D-3). These studies fall into three broad categories: 1) general references related to the applications of remote sensing for watershed modeling, but which were considered too general to list under specific parameters; 2) meteorological references to recent, general articles on the potential applications of meteorological satellite data which may play an important future role in watershed management; and 3) references covering research on watersheds or watershed modeling with LANDSAT or similar data collection systems. The IBM (1973) report listed in the general references provides useful insights into the potential of remote sensing in the area of hydrologic modeling. The more important references in this table however are found in the third category, which is comprised of those references relating to the use of data collection systems/data collection platforms capabilities. As Salomonson (1974) states in his summary of results of the Third Earth Resources Technology Satellite Symposium:

"Overall, considerable enthusiasm exists among the users of the data collection system for water resources purposes. They are enthusiastic about the general satellite data collection and relay concept and

Table D-3. Other Articles on Remote Sensing for
Watershed Modeling.

General References. Publications related to the applications of
remote sensing for watershed modeling but which were considered
too general to list under specific parameters.

     IBM, 1973
     IBM, 1975
     Molloy, Salomonson, 1973
     Pan Tek, 1975
     Burgy, et al, 1973
     Blanchard, 1973

Meteorology. Included here are general articles on the potential
applications of meteorological satellite data to watershed manage-
ment which could not be listed under specific parameters.

     Waters, 1975
     Epstein, 1975
     Oliver, Scofield, 1975

Data Collection Systems/Data Collection Platforms. Research
employing LANDSAT's Data Collection System capability.

     Halliday, Reid, Chapman, 1973
     Paulson, 1973
     Robinove, 1975
     Higer, Coker, Rogers, 1975
     Higer, Coker, Cordes, 1973
     Cooper, Bock, Horowitz, Foran, 1973
     Cooper, 1973
     Flanders, Schiesl, 1975
     Penick, 1975
     Cooper, Horowitz, 1975
     Linlor, Clapp, Meier, Smith, 1975
     Corp of Engineers, 1975 (Linlor)
     Salomonson, 1974
     Rango, McGuinnis, Salomonson, Weisnet, 1974

and this enthusiasm is due in no small part to the success of the
ERTS-1 system and the delivery of the data in near-real time."

Rango, McGinnis, Salomonson and Wiesnet writing in EOS: Transactions of
the American Geophysical Union report that:

> "During the unusually large snowmelt events that occurred during the
> spring of 1973, data from the DCP's relayed by the ERTS DCS, pro-
> vided essential snowmelt information in time periods of less than
> 1 hour. This information considerably improved the management of
> water runoff in the Salt and Verde river watersheds and lessened the
> inconvenience due to flooding in the Phoenix area."

In this article, written prior to the May 17, 1974, launch of GOES I, the
authors go on to say with respect to the Geostationary Operational Environ-
mental Satellite (GOES) that this satellite will provide an

> "...improved data collection system that will permit continuous
> 24-hour interrogation. At least 10,000 instruments (or DCP's) can
> be interrogated within a 6-hour period over the nearly one-third of
> the globe that will be in view of the satellite. Further, it will be pos-
> sible to manipulate the data at the data-receiving site and then re-
> transmit them by the GOES satellite to the appropriate analysis center."

Linlor, Clapp, Meier, and Smith (1975) discuss a microwave technique
for directly measuring snow pack wetness in remote installations. The tech-
nique, which uses satellite telemetry for data gathering, is based on the attenu-
ation of an in situ microwave beam through snow. In this work it is also
pointed out that in-situ measurement of snow wetness can be included in all
of the forecasting methods: historical, index, water-balance, and hydrologic
model. Finally, Linlor, Clapp, Meier, and Smith (1975) conclude that pas-
sive microwave systems hold great promise for satellite-based synoptic
measurements of snow areal coverage and depth; however, the measurements
are affected by the presence of liquid-phase water in the snow. They state,
however, that the in situ snow wetness measurement techniques described
in their paper can provide ground truth for the development of such passive
systems. Finally, possibly the most extensive use and evaluation of the
potential of Data Collection Systems for watershed management has been
conducted by the New England Division of the Corp of Engineers. Cooper

and Horowitz (1975) state that; based on three years experience with a 26 station network in New England, the New England Division (NED) Corp of Engineers has found real time data collection by orbiting satellite relays to be both reliable and feasible. Hydrologic parameters such as river stage, rainfall and water quality parameters are transmitted to NED within 45 minutes of acquisition by the NASA Goddard Space Flight Center, via teletype link. The only drawback related to the frequency of data reports from the LANDSAT-interrogated data collection systems (4 to 6 times daily with the 45 minute transmission lag). However, the authors state that they recognize that the present LANDSAT system is basically operating in an experimental mode to test the feasibility of data collection by orbiting satellites, noting that: "an operational system could be designed involving more than one satellite, to increase the frequency of data reporting; also, satellite ground receiving stations could be constructed in all major locales such as NED in, Waltham, Massachusetts, to permit direct and immediate receipt of the information, rather than the relay of data from NASA or other agency." The concluding remarks of this study are particularly significant. "Investigation of the LANDSAT imagery at the New England Division is part of an overall and expanding Corps of Engineers R&D program to assess the potential remote sensing capabilities for operational watershed management purposes. It is the feeling at this office that the LANDSAT Data Collection System has already made a significant contribution towards the goals embodied in this program."

4.   Conclusions

The literature on the role of remote sensing in watershed modeling and hydrologic forecasting is both diffuse and unfocused. Few papers deal directly with the applications of remote sensing to hydrologic forecasting to improve the efficiency of hydropower generation. Much of this diffuse literature deals with the role remote sensing can play in the generation of data which is the equivalent of that presently used to satisfy a specific model input parameter. Only recently, in works by Salomonson, Rango and co-authors Blanchard and personnel of the IBM Corporation, do we begin to see sharply focused research addressing the role remote sensing can play in providing input to hydrologic models.

The most significant research has been on the areal extent of snow cover, forest cover index (and other land cover data as well), the fraction of a watershed covered by streams, lakes, and riparian vegetation, and on soil moisture. In this review we have seen that remote sensing can provide significant data on 21 watershed model input parameters of importance to hydropower systems managers. Six of these parameters vary relatively little over the years. Standard conventional aerial photographic techniques can provide the needed data on these parameters. However, LANDSAT D also could play a significant role in providing data on 4 of the parameters. Owing to the low frequency of remote sensor image coverage required to document these parameters the cost-benefit leverage which can be achieved with this class of parameter is low.

Remote sensing can play a role in supplying data on 9 parameters which change at a moderate rate. Here the frequency of observation required offers limited to moderate cost-benefit potential for operational remote sensing techniques. LANDSAT D can provide data on 3 parameters (ADIMP, SARVA, VINTMR) almost unaided; it can significantly assist in the derivation of the areal extent of snow cover. In addition it can aid in the extrapolation of data concerning the depth of water which must be filled over non-pervious areas before water becomes available for free water storage (largely through inferences based on observations of surface conditions). Finally, the derivation of parameters such as water equivalent of snowpack, seasonal infiltration adjustment constant, and precipitation data station weights, may be accomplished but will require the development of a system of analysis which incorporates data from an appropriate mix of sensor systems.

Finally, remote sensing can play a role with respect to the measurement of 6 parameters which vary dynamically (i.e., weekly, daily, hourly or more frequently). These highly variable parameters offer potentially large cost-benefit leverage if monitoring by remote sensing proves operationally feasible. To date, there is little firm evidence to verify the feasibility of utilizing air/space borne sensors for measurement of these variables in non-uniform, mountainous watersheds. Much additional research is required to establish a firm role for remote sensing.

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